Final

Functional Relationships for the Ecosystem Functions Model Sacramento-San Joaquin Rivers Basin Comprehensive Study

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SECTION 1. INTRODUCTION

Purpose of Report

The purpose of this report is to recommend specific relationships between physical or hydrologic variables and biological variables for use in an ecosystems function model (EFM) for the lowland river-floodplain systems of the Sacramento-San Joaquin Rivers Basin. This report is the draft of the final report on recommended EFM relationships as specified in the scope of work, dated March 29, 2000 (revised April 14, 2000), attached to Delivery Order No. 0022 under Contract DACW05-98-D-0020, between the U.S. Army Corps of Engineers (Corps) (Sacramento District) and Jones & Stokes.

Purpose and Nature of Ecosystems Function Model

The concept of an EFM for the Sacramento-San Joaquin Rivers Basin is described in detail in “Ecosystems Functions Model—Conceptual Design Report” (Jones & Stokes Associates 1999), published as Appendix D of the Corps’ “Phase I Documentation Report” for the “Sacramento-San Joaquin Rivers Basin Comprehensive Study”. The purpose of the proposed EFM is to understand how actions to reduce flood damage can be implemented to maintain or enhance terrestrial and aquatic habitat values of lowland river-floodplain ecosystems in the Sacramento-San Joaquin Rivers Basin.

The EFM is a set of functional relationships between river flow/floodway morphology and the biological communities of these lowland channel-floodplain systems. It is envisioned that existing and predicted flow and floodway data would be processed through the functional relationships to produce key indicators of biological change. The EFM would therefore indicate the direction of biological change (and in many cases, the magnitude of biological change) that would result from implementing flood-damage reduction measures or enviornmental restoration. Measures that could be modeled, therefore, are those that change the flow regime or the character of the floodway. The model anticipates that most of the changes in flow would involve floodflows, although some knowledge of low-flow hydrography would be needed. The model would predict biological changes on a landscape level, using flow and floodway data at 0.2-mile intervals. It would predict long-term adjustments of biological systems to physical/hydrologic changes, which may not fully materialize for decades.

Organization of Conceptual Model

The functional relationships recommended in this report define the organization of the EFM. The EFM would consist of two major elements: the aquatic ecosystem and the terrestrial ecosystem. The model would include the effects of seasonal overbank flows on both systems; in fact, the biological effects of overbank flow are a major focus of the recommended relationships.

The terrestrial element would consist of three parts: the extent of potential riparian and wetland zones, rates of ecosystem change in these communities, and wildlife habitat values of these dynamic systems. Predicted changes in potential riparian/wetland zones would be inferred spatially by overlying suitability maps reflecting particular attributes, as identified in several recommended relationships. Other recommended relationships would specify how several ecosystem processes would be temporally affected (i.e., fluctuations in the rates of change). A wildlife response model would consist of applying a set of relationships that specify key wildlife habitat suitability indices.

The aquatic element would consist of two parts: in-channel habitats and seasonally inundated floodplains and flood bypasses. Recommended relationships focus on factors that affect all the life stages of salmonids and Sacramento splittail (as representatives of the entire aquatic community). The in-channel element includes relationships that reflect the dependence of suitable substrate, instream cover, and bank vegetation on changes in flow and morphologic parameters. The floodplain element incorporates conditions for suitable overbank flows to benefit floodplain spawning, rearing, and avoidance of stranding, and predicts spatial changes in the extent of suitable floodplain habitat. All of the model elements are listed in Table 1-1.

Table 1-1. Elements of Ecosystem Function Model for Sacramento-San Joaquin Rivers Basin, and Their Disposition

Ecosystem	Element	Sub-Element	Corps Recommendation for Disposition	Treatment in this Report
Terrestrial	A. Potential riparian and wetland zones	A-1. Substrate characteristics	Defer	Partially developed
		A-2. Depth of water table	Develop	Developed
		A-3. Flood events suitable for plant germination and establishment	Develop	Developed
		A-4. Scour regime of riparian zones	Develop	Developed
		A-5. Scour and inundation of active channel habitats	Develop	Develop
Terrestrial	B. Rates of ecosystem change	B-1. Rates of channel migration	Defer	Developed
		B-2. Frequency and intensity of flood scour	Defer	Incorporated into A-4 and A-5
		B-3. Tendency for aggradation or degradation	Defer	Deferred
		B-4. Rate of overbank germination flows	Develop	Incorporated into A-3
		B-5. Rates of vegetation succession	Defer	Deferred
Terrestrial	C. Connectivity to aquatic habitats		Develop	Incorporated into Aquatic II C
Terrestrial	D. Land-use constraints		Defer	Deferred
Terrestrial	E. Wildlife habitat suitability		Defer	Deferred
Aquatic: I. Stream channel	A. Adult migration	A-1. Passage depth and velocity	Defer	Deferred
		A-2. Passage barriers	Defer	Deferred
		A-3. Water temperature	Defer	Deferred
Aquatic: I. Stream channel	B. Adult holding and spawning	B-1. Holding habitat abundance	Defer	Deferred
		B-2. Spawning substrate abundance	Defer	Deferred
		B-3. Water temperature	Defer	Deferred
Aquatic: I. Stream channel	C. Egg incubation	C-1. Spawning habitat scour	Defer	Deferred
		C-2. Spawning habitat desiccation	Defer	Deferred
		C-3. Intra-gravel flow	Defer	Deferred
		C-4. Water temperature	Defer	Deferred

Ecosystem	Element	Sub-Element	Corps Recommendation for Disposition	Treatment in this Report
Aquatic: I. Stream channel	D. Juvenile rearing and movement	D-1. Early rearing habitat abundance	Develop	Deferred
		D-2. Rearing habitat abundance	Defer	Deferred
		D-3. Water temperature	Defer	Deferred
	E. Juvenile migration	E-1. Rearing habitat abundance	Develop	Developed
		E-2. Diversion loss	Defer	Deferred
		E-3. Passage-barriers	Defer	Deferred
		E-4. Water temperature	Defer	Deferred
Aquatic: II. Flood-plains and flood bypasses	A. Adult migraton	A-1. Passage barriers	Defer	Deferred
Aquatic: II. Flood-plains and flood bypasses	B. Adult spawning and egg incubation	B-1. Spawning habitat abundance	Develop	Developed
Aquatic: II. Flood-plains and flood bypasses	C. Juvenile rearing and movement	C-1. Rearing habitat abundance	Develop	Developed
		C-2. Predation	Defer	Deferred
		C-3. Habitat connectivity	Defer	Developed

Use of the Model

The model is intended to predict differences between without-project and with-project conditions in river reaches that would be affected by implementation of flow or floodway management measures. The functional relationships recommended are tools that permit consideration of modifications of proposed actions that may avoid, reduce, or enhance biological response. Using input variables of flow and morphology, the model permits direct identification of changes in flow regime and morphology that would result in particular benefits or adverse effects on key attributes of the river-floodplain ecosystem. The model outputs indicators of ecosystem health, which include changes in the extent of suitable riparian and seasonally inundated aquatic habitats, in key river channel conditions, and in rates of ecosystem processes.

Required Inputs

The identification of the recommended relationships required careful consideration of model input requirements. Model inputs must be flow-regime or morphology parameters that likely would be changed by some of the types of measures under consideration in the Comprehensive Study. Another consideration is the availability of information about flow regime and floodway morphology that would reflect changes caused by measures. Most of the relationships require data on daily streamflows over representative periods of record to represent both the historic and predicted flow regimes. The relationships also require data on flood magnitude and frequency, from bankful to larger floods, and data about hydraulic relationships at the series of cross sections being used for flood-routing analyses in the Comprehensive Study. Most of the relationships require higher-flow data already being developed for the flood-damage assessments, but some of them require a knowledge of the elevation of the average low-flow water surfaces. Some data would also require data on existing river and floodplain sediments, which is relatively easy to compile.

Model Mechanism

Model mechanisms include a computational program and a geographic information system (GIS). The recommended relationships would be incorporated into new programming code for computerized analyses of historical and with-project simulated daily flow datasets. Current scientific programming language suitable for application on a PC or local computer network would be used. Outputs in the form of elevation-frequency data would be fed to a GIS coverage of the project reach. The GIS would use the detailed digital terrain model prepared for the Comprehensive Study. By intersecting with the digital terrain model (DTM) elevational data resulting from application of the recommended relationships, a series of maps and composite maps would be produced to depict changes in ecosystem suitability. Specifically, maps would show without-project distribution, with-project distribution, and change in:

a. potential riparian and wetland zones, according to the five vegetation zones identified;

b. channel width in relation to potential riparian zones during average low-flow conditons;

c. floodplain area providing suitable habitat for splittail;

d. floodplain area providing suitable rearing habitat for salmon and splittail; and

e. potential fish entrapment areas of the floodplain.

Performance Monitoring

Effects of measures to reduce flood damage and restore environment should be monitored to determine the degree to which program goals are met. Monitoring should include monitoring of the specific indicators (relational outputs) recommended in this report. Long-term monitoring would be required because some of the relationships involve predictions of average habitat location over several decades.

Deferral of Some Model Elements

Some model elements have a higher priority for development than others. The Corps has determined that certain elements should be developed now, whereas others should be deferred (Table 1-1). Those elements given priority are generally those most closely related to floodflow management; therefore, they focus on ecosystem responses to floodplain inundation. However, fish-rearing habitat effects at lower flows have been developed as well.

Organization of This Report

Two sections follow this section: recommended relationships for the terrestrial element and those for the aquatic element. A separate appendix for each element is also included. The appendices present reviews of other EFM efforts, relevant scientific literature and anecdotal sources, and the rationale for selecting each of the recommended relationships. A third appendix addresses the hydrologic and hydraulic data and analyses needed to translate the recommended relationships into an operational EFM.

SECTION 2. RECOMMENDED PHYSICAL-BIOLOGICAL RELATIONSHIPS AND ASSUMPTIONS FOR THE TERRESTRIAL ECOSYSTEM MODEL

A terrestrial ecosystem model would have five major elements:

a. potential riparian and marsh/wetland zones,
b. rates of ecosystem change,
c. connectivity to aquatic habitats,
d. land use constraints, and
e. wildlife habitat suitability.

As noted in Section 1, development of some of these elements has been deferred at the recommendation of the Corps.

A. Potential Riparian and Wetland Zones

Several criteria (discussed below) should be used to define the spatial extent of areas that have, or would have in response to an action (measure), physical characteristics suitable for development of good riparian or wetland habitat when considered over the long term. The areas that have or would have these characteristics are:

- Zone 1. Active Channel Habitats (riverwash and herbaceous riparian habitats)
- Zone 2. Riparian Willow Scrub
- Zone 3. Cottonwood Riparian Forest
- Zone 4. Mixed Riparian Forest
- Zone 5. Freshwater Marsh and Associated Wetlands

Terrestrial habitats within the active channel zone (Zone 1) include sand- and gravel bars (riverwash) that may be bare or may, at certain times of the year, be vegetated by herbaceous species and small seedlings of woody plants. Of all terrestrial habitats, this zone is most frequently inundated and it is exposed to the most flood disturbance and scour. Geomorphically, it is the zone of bankfull discharge.

On surfaces at higher elevations bordering the river channel, the reduced growing-season inundation and frequent flood disturbance and scour promotes the development of riparian willow scrub (Zone 2). It consists of narrow-leaved willow (*Salix exigua*) and seedlings and saplings of cottonwood and other willow species.

The cottonwood riparian forest (Zone 3) occurs on sites with less frequent disturbance than the riparian willow scrub community. Mature vegetation is dominated by Fremont cottonwood (*Populus fremontii)* and Goodding's black willow (*Salix gooddingii).*

The mixed riparian forest zone (Zone 4) usually occurs at still higher elevations and at greater horizontal distance from the river channel than the cottonwood riparian forest. In addition to Fremont cottonwood and Goodding's black willow, box elder (*Acer negundo* var. *californicum*, California black walnut (*Juglans californica* var. *hindsii)*, western sycamore (*Platanus racemosa)*, and Oregon ash (*Fraxinus latifolia*) are typically found here. In this zone, valley oak (*Quercus lobata*) may be the dominant species on the highest floodplain and on terrace surfaces with the least physical disturbance. When dominated by valley oak, this zone differs from the upland valley oak savannah by the presence of the riparian species in the mixed riparian forest zone in the understory.

In the absence of natural events destructive of vegetation (i.e., flood scour, channel migration, prolonged inundation, fire, windthrow), there is a tendency for the plant communities to undergo succession from the early-successional zones to later-successional zones. Thus, riparian willow scrub (Zone 2) tends to succeed toward cottonwood riparian forest (Zone 3), which in turn tends to succeed toward mixed riparian forest (Zone 4). Periodic disturbances, however, tend to set the successional process back toward the earlier successional zones.

The potential freshwater marsh zone (Zone 5) corresponds to sites on clayey soils inundated for long periods and subject to significant flow velocity only during major flood events. This zone is dominated by *Scirpus* and *Typha* species. It includes both the large overflow basins and smaller features, such as oxbows.

The criteria that determine the potential area of each zone in a particular reach are:

1. substrate characteristics,
2. depth to water table,
3. flood events suitable for plant germination and establishment,
4. scour regime of potential riparian zones, and
5. scour and inundation of active channel habitats.

Assumptions and relationships for these criteria, or subelements, are described in the following sections.

A-1. Substrate Characteristics. The Corps recommended that development of this subelement be deferred. However, it is presently retained because is an integral part of the five subelements that define "potential riparian/wetland zones".

Substrate characteristics, principally sediment/soil texture, strongly affect the suitability of a site for the development of various vegetation types, although such characteristics do not necessarily exclude the possible establishment of other types less suited to the particular substrate.

Assumptions and Relationships:

1. The freshwater marsh zone (Zone 5) is optimally suited to Helley and Harwood's (1985) Geologic Unit *Qb* (Quaternary basin deposits), Marchand and Allwardt's (1978, 1981) equivalent geologic mapping units for the eastern San Joaquin Valley, or, in western San Joaquin Valley gap areas, clayey soil series mapped by the Soil Conservation Service (SCS).

2. All riparian forest and scrub zones (Zones 2, 3, and 4) are optimally suited to Geologic Unit *Qa* (Quaternary river alluvium), equivalent eastern San Joaquin mapping unit *Hal*, or, in western San Joaquin Valley gap areas, silty-sandy soil series mapped by SCS.

3. The mixed riparian forest zone (Zone 4) is also optimally suited to resistant Pleistocene sediments (e.g. Tehama, Modesto, Riverbank formations) mapped by Helley and Harwood (1985) and Marchand and Allwardt (1978, 1981). For western San Joaquin Valley gaps areas, SCS soil series corresponding to these resistant formations would need to be identified.

4. For the active channel zone, see "A-4 Scour Regime" and "A-5 Growing Season Inundation" below.

5. All other areas are considered suitable for upland types.

(Some adjustments to these recommended relationships may need to be made during development of the model at specific pilot reaches, as warranted by comparison of existing vegetation and the geologic/soil map units.)

A-2. Depth of Water Table. Woody riparian species require access to the water table throughout the growing season, and marsh vegetation is only sustained where the water table is very shallow. Local data on depth to groundwater should be assembled wherever it is available.

Assumptions and Relationships:

1. In absence of local data, the water table can be assumed to lie approximately at the elevation of the average August water surface elevation, as inferred at each cross section.

2. Riparian zones (Zone 2, 3, and 4) apparently require a maximum depth to groundwater of 11–21 feet, with the range reflecting uncertainty in the present level of understanding of this subelement. For purposes of establishing a maximum limit for potential riparian zones, we recommend use of a maximum elevation above the water table of approximately 21 feet. For purposes of establishing a limit for potential *prime* riparian zones (i.e., zones exhibiting continuous cover, desirable native species, and structural diversity), we recommend use of a maximum elevation above the water table of approximately 16 feet.

3. Willow scrub and cottonwood riparian forest (Zones 2 and 3) require that the decline of seasonally high water tables following initial establishment of willow and cottonwood

seedlings be sufficiently slow to promote root growth without wilting; this constraint is addressed in Section A-3.

4. Freshwater marsh (Zone 5) requires a water table within 1 foot of the surface in an average September, which is approximately equivalent to the typical capillary rise in sandy-silt alluvial substrates.

A-3. Flood Events Suitable for Plant Germination and Establishment. Areas potentially suitable for germination and establishment of riparian willow scrub and the cottonwood riparian forest communities (Zones 2 and 3) are defined by the frequency of inundation during the seed release period for the cottonwood and willow species and by hydrologic events immediately following the seed release period.

Assumptions and Relationships:

1. Overbank flow for germination must occur between mid-April and mid-August. This period differs for the different riparian tree species of concern. For example, the main seed release period for Fremont cottonwood occurs from mid/late April through late May/early June, whereas the seed release period for Goodding's black willow occurs from late May through mid-August.

2. For successful plant establishment, the rate of hydrograph decline during the first growing season must not exceed 1.5 inches per day. This criteria should be met during each week of the growing season following deposition of seed on sites otherwise suitable for germination (i.e., hydrograph decline should not exceed 0.88 feet/week).

3. If an action increases the average time interval between hydrologic events that are optimal for germination and establishment (i.e., meeting criteria #1 and #2 above), the proportion of mixed riparian forest (Zone 4) will increase, whereas if a project decreases the average time interval between suitable hydrologic events, the proportion of cottonwood riparian forest (Zone 3) will increase. Over the long term, the approximate boundary between Zones 3 and 4 will be located where the stage of overbank flows meeting criteria #1 and #2 above recurs with a return period of approximately 40 years.

4. Plants that germinate too close to the low-flow shoreline will be subsequently removed by scour or inundation; this phenomenon is addressed in Section A-5.

A-4. Scour Regime of Riparian Zones. Scour of vegetation during flood events may remove vegetation and hence set back the riparian vegetation succession sequence. In particular, the average locations of boundaries between riparian willow scrub and cottonwood riparian forest (Zone 2/3 boundary) and between cottonwood riparian forest and mixed riparian forest (Zones 3/4 boundary) depend upon the frequency of scouring flows relative to the prevailing flow regime.

Assumptions and Relationships:

One of two different approaches may be taken:

1a. Because shear stress is proportional to flow depth at a given cross section, changes in scour potential and average locations of boundaries of the various riparian zones can be approximated by comparing the distribution of flow depths over the floodplain for with-project and without-project flows having the same return period. The pattern of flow depth for the without-project condition for a particular overbank flow (e.g. 10-year return period flow) can be assumed to control the existing Zones 2/3 and 3/4 boundaries. Changes in the pattern of flow depth for the with-project flow having the same return period can be used to predict the change in the location of the these two zone boundaries.
or,

1b. Using a surrogate for scour effects, changes in scour potential and average locations of boundaries of the various riparian zones can be approximated by changes in area of inundated floodplain for with-project and without-project flows having the same return period. The return periods of the without-project flows corresponding to the existing locations of the two zones boundaries are determined, and the stages of the with-project flows having the same return periods define the locations of the with-project boundaries.

Note: for both approaches, existing zones boundaries should not be field mapped within five years of a major flood event, because major floods will temporarily shift vegetation zone boundaries. If mapping during such a period is necessary, pre-flood aerial photography should be used.

A-5. Scour and Inundation of Active Channel Habitats. Increases in water surface elevation during the growing season causes death of woody riparian shrubs and trees due to anoxia in the root zone, interference with leaf transpiration, or depletion of energy reserves. Inundation of recently-established seedlings at the margins of the active channel zone (Zone 1) may cause these substrate to remain unvegetated, thereby controlling the lower limit of the potential riparian scrub zone. This zone may widen or narrow depending upon changes in the low-flow regime during the growing season.

In addition, the presence of frequent, intense scour ("riverwash") also determines the lower elevational limit of the potential riparian scrub zone. Both factors, inundation and scour potential, should be examined for the with-project and without-project conditions, and the highest elevation of these two effects should be used to determine the average boundary between the active-channel habitat and the riparian willow scrub zones (Zones ½ boundary).

Assumptions and Relationships:

1. Increases in river stage during lower-flow period of the growing season provide one control on the extent of the active channel habitats (Zone 1). The highest stage sustained for at least 21 days during the period from mid-July through September defines the zone of growing season inundation that will preclude the establishment of woody riparian vegetation. Stages for without-project and with-project conditions can be compared to provide the first indication of changes in the width of Zone 1.

2. Scour effects controlling the width of the active channel habitat (Zone 1) can be evaluated by one of the two methods analogous to those described above in Section A-4 for estimating changes in Zones 2/3 and 3/4 boundaries. That is to say, changes in flow depths for a given return-period flow, or changes in extent of inundation for a with-project flow having the same return period of the without-project flow inundating the existing Zone 1, can be used to predict changes in width of the active channel habitat zone.

3. The highest elevation determined from each of the two assumptions/relationships above can be used to define expected changes in the extent of the active channel habitat zone (Zone 1).

B. Rates of Ecosystem Change

The dynamic nature of riparian systems is key to ecosystem health. The rates of habitat renewal and other change, to be considered as average rates over periods of decades rather than as specific spatial-temporal predictions, depends upon 1) rate of channel migration, 2) rate of other vegetation disturbance (i.e. floodplain scour and deposition, disease, windthrow, fire, etc.), 3) rate of events suitable for germination and plant establishment, and 4) vegetation successional changes. Rates of vegetation disturbance probably cannot be estimated but are considered to be significant only in the absence of a suitable rate of overbank germination. The tendency for increased floodplain scour or deposition can be estimated, however.

B-1. Rates of Channel Migration. The Corps recommended that development of this sub-element be deferred. However, it is presently retained because it is also part of the Sub-element D-1 of the aquatic element, which has not been deferred.

Channel migration is commonly accompanied by the development of "point bars", which provide fresh substrate for the germination and establishment of cottonwood riparian forest and riparian scrub (Zone 1), and corresponding bendway erosion, which destroys existing riparian habitats (Zones 2-4) or wetland habitats (Zones 5). To estimate potential change in rates of channel migration, the degree of natural channel migration in the subject reach must first be estimated (see Table A-5). The direction of change as a result of an action is then estimated by determining the change in a specific flow parameter that is related to rate of channel migration.

Assumptions and Relationships:

1. The identification of reaches where channel migration potentially occurs and the differentiation of the relative rates of migration in these reaches can be based on distribution of bedrock and resistant Pleistocene formations, tectonic factors, and the reach's flow regime (Table A-5). The existing distribution of bank protection should not necessarily be considered a constraint to potential channel migration because rock removal is a potential environmental restoration measure. Where rock removal is not under consideration, existing rock would be considered sufficient to prevent channel migration.

2. For the various reaches, the average rate of channel migration is approximately related to floodflows with return periods between 1.5 and 5 years. If an action results in an increase in the 1.5-year and the 5-year flow, the rate of channel migration will increase. If these flows decrease, the rate of channel migration will decrease. The exact relationship between these flows and the rate of migration is variable, however, so that a reliably predictive function relating the two cannot be formulated.

3. Increased channel migration will result in more rapid habitat renewal, while decreased channel migration will result in slower habitat renewal. Where existing rates of migration are near or exceed the rate at which later successional zones (i.e., Zones 3 and 4) develop in a particular reach, increased rates of migration are generally detrimental to ecosystem functions. Where existing rates are less that rates of succession, increased rates of migration are beneficial.

B-2. Frequency and Intensity of Flood Scour. Frequency of flood scour has been incorporated into two of the sub-elements that define potential riparian zones; see sub-elements A-4 and A-5.

B-3. Tendency for Degradation or Aggradation. Deferred.

B-4. Rates of Overbank Germination Flows. Frequency of germination flows has been incorporated into an element that defines the potential riparian willow scrub zone (Zone 2) and the cottonwood riparian forest zone (Zones 3); see sub-element A-3.

B-4. Rates of Vegetation Succession. Deferred.

C. Connectivity to Aquatic Habitats

The degree of connection of riparian habitats to aquatic habitats in terms of periodic allochthonous inputs and providing seasonal rearing habitats depends upon the extent, timing, depth, duration, rate of recession, and frequency of overbank flows. These variables also govern the availability and suitability of seasonal wetlands for wildlife. The former is addressed in “Section 3. Aquatic Ecosystem Model”, Section II, element C. Development of the latter is deferred.

D. Land-Use Constraints. Deferred.

E. Wildlife Habitat Suitability

Wildlife habitat suitability depends primarily upon:

- type and acreage of potential and actual habitats (Sections A and D),
- structural characteristics of those habitats (Section B-5),

- rate of channel migration (e.g., for bank swallow) (Section B-1), and
- the floodplain inundation regime (Section C).

As described in Section A above, the model will produce anticipated changes in wetland and riparian habitats resulting from an action. Regarding Section B-5 above, structural characteristics of seral stages of riparian habitats and relative proportions of various stages has been deferred. As described in Section C, seasonal inundation and wetland regime can be quantified. These outputs might be used to assess wildlife habitat suitability using one or more of the following methods:

- assessing changes in extent of suitable habitat for a wide variety of species based on known wildlife habitat relationships (WHR);

- predicting changes in habitat value by application of selected existing species or community habitat suitability index (HSI) models (these models generally are developed for application in habitat evaluation procedures [HEP] methodology); and/or

- predicting changes in habitat value by application of HSI models developed specifically for assessing wildlife habitat suitability based on EFM outputs.

Development of these methods is deferred.

SECTION 3. RECOMMENDED PHYSICAL-BIOLOGICAL RELATIONSHIPS AND ASSUMPTIONS FOR THE AQUATIC ECOSYSTEM MODEL

Aquatic ecosystem values are primarily related to the abundance and distribution of socially and politically important fish species, including species important to commercial and sport fisheries and species listed under the federal and California Endangered Species Acts. Relationships included in the aquatic element of the EFM should therefore provide a measurement of ecosystem attributes that affect the abundance and distribution of fish species. Relationships identified in this report are selected based on two broad premises. First, habitat abundance and quality affect fish population abundance and distribution, food resources available, and the effects of predation and competition. Second, ecosystem processes and structure, primarily geomorphic and hydrologic, determine the structure and dynamics of the river and floodplain and the subsequent creation and maintenance of fish habitat.

The aquatic ecosystem model has two primary geographic elements, the stream channel and the floodplain, including the flood bypasses. The stream channel element supports aquatic species throughout the year. In the Sacramento-San Joaquin River system, floodplain and flood bypasses provide essential seasonal habitats for aquatic species that allow expression of life history types that are different than would occur in the stream channel alone. Greater life history diversity contributes to increased species population productivity, potentially increasing resilience and resistance of the population to annual fluctuations in abundance under variable environmental conditions. In addition, fish species diversity and population abundance is generally higher with increased floodplain area and duration of floodplain inundation.

I. STREAM CHANNEL

The stream channel model element potentially has four major sub-elements, representing life history events in the life cycle of chinook salmon. Chinook salmon are selected as the representative species for the stream channel because they are sensitive to an important cross section of ecosystem attributes, are native to the system and use a range of habitats important to other native species in the aquatic community, and are targeted for restoration under the federal and California Endangered Species Acts, CALFED, and the Central Valley Project Improvement Act. Maintenance of habitat integrity and diversity is assumed to preserve the resilience of the associated biological community. The relationships identified include geomorphic and hydrologic elements that affect the physical variability of aquatic habitats.

The four major life history events for chinook salmon are adult migration, adult holding and spawning, egg incubation, and juvenile rearing and movement. Restoration and maintenance of chinook salmon populations requires successful completion of all life history events. Development of relationships for adult migration, adult holding and spawning, and egg incubation elements has been deferred as described in Section 1. Relationships for juvenile rearing and movement are presented in this section.

E. Juvenile Rearing and Movement

Key factors for successful rearing and movement of juvenile fish include rearing habitat abundance, suitable water temperature, minimization of diversion losses, and absence of passage barriers.

E-1. Rearing Habitat Abundance. The flow velocity, depth, and cover components of suitable rearing microhabitats are driven by ecosystem-level processes and structure, including hydrology, sediment movement, channel morphology, and extent of woody riparian vegetation. Thus, key relationships at the ecosystem level that define suitable rearing habitat involve 1) flows needed to maintain suitability of spawning gravel substrates for early rearing, 2) flows sustaining sufficient channel migration to assure maintenance of channel complexity, and 3) presence of woody bank vegetation to provide overhead cover and instream cover recruitment during channel migration.

Assumptions and Relationships:

1. The movement and supply of gravel 2–15 cm in diameter to a river reach must be sufficient to maintain existing gravel substrates and bedform that provide rearing habitat for juvenile chinook salmon. Periodic scour is needed to maintain invertebrate communities and to remove fines that fill the spaces between gravel particles. To maintain juvenile rearing habitat quality and quantity provided by gravel substrates, peak flows must mobilize gravels up to at least 10 cm in diameter during nearly all years. The peak flows must occur in the rearing reaches where source proximity and stream gradient permits the presence of gravel substrates. An incipient motion analysis can be applied in suitable reaches to determine changes in frequency of flows mobilizing 10 cm diameter particles between without-project and with-project conditions.

2. Channel migration rates promotes channel-habitat complexity, particularly by promoting recruitment of instream woody material. The without-project and with-project flow regimes can be compared to determine if channel migration will increase or decrease with application of an action. The average rate of channel migration is approximately related to floodflows with return periods between 1.5 and 5 years. If an action results in an increase in the 1.5-year and the 5-year flow, the rate of channel migration will increase. If these flows decrease, the rate of channel migration will decrease. Increased channel migration throughout most of the Sacramento-San Joaquin River system is considered ecologically beneficial, while decreased channel migration is considered ecologically detrimental.

3. To provide overhead cover and instream-cover recruitment during channel migration, river banks and floodplains should support woody riparian plants. The presence of woody bank vegetation is dependent upon the proximity of the woody riparian zone to the channel during the low-flow periods. Project-induced changes in this proximity can be measured by projected changes in the location of the lower boundary of the potential riparian zone, as described in sub-element A-5 of Section 2 (terrestrial EFM) relative to projected changes in

the location of the average-August edge of water. Increased proximity is ecologically beneficial.

II. FLOODPLAINS AND FLOOD BYPASSES

The floodplain and flood bypass model element has three sub-elements representing life history events in the life cycle of chinook salmon and splittail. In addition to the stream channel habitat discussed above for chinook salmon, floodplain and flood bypasses provide important rearing habitat for juvenile chinook salmon. Splittail are included along with chinook salmon in development of relationships because their habitat needs encompass additional attributes relative to timing, magnitude, and duration of flood events. Like chinook salmon, splittail are native to the system and they are targeted for restoration under the federal Endangered Species Acts and by CALFED.

The major life history events include adult migration for chinook salmon, adult spawning and egg incubation for splittail, and juvenile rearing and movement for chinook salmon and splittail. Restoration and maintenance of chinook salmon and splittail populations requires successful completion of all life history events. Development of relationship for the adult chinook salmon migration element has been deferred as described in Section 1. Key habitat relationships presented below are focused on floodplain inundation potentially important to both chinook salmon and splittail.

B. Adult Spawning and Egg Incubation

Seasonally inundated floodplain and flood bypasses provide important spawning habitat for splittail.

B-1. Spawning Habitat Abundance. The availability of spawning habitat for splittail is related to flood timing, magnitude, duration, and frequency relative to floodplain and flood bypass morphology.

Assumptions and Relationships:

1. Increasing the inundated area of vegetated floodplain and flood bypasses, by increasing the magnitude or frequency of overbank flows or floodplain area, increases fish population abundance. Increasing the ratio of inundation perimeter to area increases the value of the inundation habitat.

2. Terrestrial vegetation in the floodplain and flood bypasses should be inundated for at least 21 to 28 consecutive days between February and May to provide habitat for splittail

spawning. (Flooding prior to February may be important to attract adults upstream and to provide forage habitat for adult splittail, but adult splittail migration is currently not well understood.) A minimum multi-year recurrence frequency for flows needed to inundate the floodplain is required to sustain splittail populations; a 2-3 year return period will support adequately-frequent spawning, while a 4-year return period may not (i.e. a maximum suitable return period of 3 years may be assumed). The without-project and with-project flow regimes can be examined to determine the maximum stage of overbank flows meeting these timing, duration, and frequency criteria for each condition, and changes in extent of inundation, and changes in the ratio of perimeter to area, meeting these criteria can be therefore be depicted.

3. The area of suitably frequent inundation should be overlain with the depiction of potential riparian zones (Zones 2-5) and mapping of upland and agricultural vegetation, for without-project and with-project conditions, to determine changes in the areas of inundation for each vegetation type.

C. Juvenile Rearing and Movement

Seasonally inundated floodplain and flood bypasses provide important rearing habitat for both juvenile chinook salmon and splittail. Rearing of juvenile splittail and chinook salmon coincides with winter flood events that inundate floodplains and flood bypasses. High flows also appear to increase the density of juvenile chinook salmon in downstream habitats, including the large expanses of floodplain and flood bypasses in the lower segments of large rivers. Key factors affecting rearing success include habitat abundance, predation, and connectivity with the river channel.

C-1. Rearing Habitat Abundance. The area of habitat for rearing by juvenile chinook salmon and splittail is related to flood timing, magnitude, frequency, and duration relative to floodplain and flood bypass morphology. In addition, floodplain and flood bypass habitat offer protection from large piscivorous fish such as striped bass. Key features of rearing habitat that serve to exclude predatory fish include relatively shallow depths, dense cover provided by flooded vegetation, and the temporary availability of floodplain habitat which prevents development of high predatory fish densities.

Assumptions and Relationships:

1. Increasing the inundated area of vegetated floodplain and flood bypasses, by increasing the magnitude or frequency of overbank flows or floodplain area, increases fish population abundance. Increasing the ratio of inundation perimeter to area increases the value of the inundation habitat.

2. Terrestrial vegetation in the floodplain and flood bypasses should be inundated from December to May to provide rearing habitat for juvenile chinook salmon and splittail.

Inundation durations of greater than 8 weeks are optimal. For splittail, these conditions must occur in the same year when the spawning conditions are met (see Section B-1 above). Thus, a maximum suitable return period of 3 years may be assumed. The without-project and with-project flow regimes can be examined to determine the maximum stage of overbank flows meeting these timing, duration, and frequency criteria for each condition, and changes in extent of inundation, and changes in the ratio of perimeter to area, meeting these criteria can be therefore be depicted.

3. The area of suitably frequent inundation should be overlain with the depiction of potential riparian zones (Zones 2-5) and mapping of upland and agricultural vegetation, for without-project and with-project conditions, to determine changes in the areas of inundation for each vegetation type.

C-3. Habitat Connectivity. Juvenile chinook salmon and splittail must return to the main river channel after rearing in floodplain and flood bypass habitat or they will die. Connectivity is the opportunity for fish to return to the main river channel during the period of falling stage after a flood event. Connectivity is dependent on floodplain and flood bypass topography. Suitable floodplain rearing habitat should slope to a main channel or slough to facilitate complete drainage and avoid stranding of adults, larvae, and juveniles in depressions or other low-lying floodplain features.

Assumptions and Relationships:

1. The area of isolated ponds with a depth exceeding 1 foot when flow corresponds to the mean April flow or the mean May flow, whichever is highest, as well as the area that drains through such ponds, is an indicator of connectivity. Increases in one or both of these acreages in considered ecologically detrimental, while reductions are considered ecologically beneficial. Without-project and with-project floodplain topography can be compared based on this indicator. Actions that include floodplain grading intended to reduce detrimental conditions can readily be incorporated into this analysis.

2. Connectivity is assumed to have minimal effect on survival when inundation of the flood plain and flood bypasses lasts through April for chinook salmon and May for splittail. The without-project and with-project flow regimes can be examined to determine changes in the frequency of such long-duration events.

APPENDIX A. DERIVATION OF RELATIONSHIPS RECOMMENDED FOR THE TERRESTRIAL ECOSYSTEM MODEL ELEMENT

As described in the main text of this report, a terrestrial ecosystem model would have the following major elements and sub-elements. As described in Section 1, development of some of these elements has been deferred.

A. Potential riparian and wetland zones

- A-1. Substrate characteristics
- A-2. Depth of water table
- A-3. Flood events suitable for plant germination and establishment
- A-4. Scour regime of riparian zones
- A-5. Scour and inundation of active channel habitats

B. Rates of ecosystem change

- B-1. Rates of channel migration
- B-2. Frequency and intensity of flood scour (deferred)
- B-3. Tendency for degradation or aggradation (deferred)
- B-4. Rates of overbank germination flows
- B-5. Rates of vegetation succession (deferred)

C. Connectivity to aquatic habitats

D. Land use constraints (deferred)

E. Wildlife habitat suitability (deferred)

This appendix describes, for each of these elements, the results of our literature review, followed by the rationale we used in determining the relationships recommended in the main text of this report.

REVIEW OF EXISTING MODELS

Numerous models linking ecosystem processes and vegetation structure have been developed, yet few are directly relevant to predicting impacts of hydrologic alterations to terrestrial riparian systems.

Pearlstine et al. (1985) created a bottomland hardwood forest succession simulation model (FORFLO) to study the impact of an altered hydrologic regime on the coastal forested floodplain surrounding the Santee River in South Carolina. Relationships between hydrologic variables and seed germination, tree growth, and tree mortality for individual species were used to predict the direction of succession. This simulation was then coupled with a GIS to allow a visual depiction of predicted riparian vegetation changes. The FORFLO model was itself developed by modifying previously existing forest models, FORET (Shugart and West 1977), and JABOWA (Botkin et al. 1972). Relationships for the FORFLO model were based on species native to South Carolina, and the model therefore applies mainly to deciduous forests of the southeastern U.S.

Franz and Bazzaz (1977) devised a vegetation response model to predict the relative impacts of different reservoir designs on forest vegetation. This model used existing distribution of individual tree species on a flood-frequency gradient to evaluate relative flood tolerance. Difference in with- and without-project stage probabilities were then calculated and shifts in individual species probabilities predicted. Toner and Keddy (1997) quantified numerous flood-related variables to determine the best predictors of vegetation type in riparian zones along the Ottowa River, Canada. Two variables - last day of the first flood (correlated to flood duration), and time of the second flood (growing season inundation) produced the best predictive model. Similar modeling approaches have been used by Harris et al. 1985 and Auble et al. (1994) and Johnson et al. (1999).

The model developed by Auble et al. (1994), using a direct gradient method, was used for predicting impacts to riparian vegetation resulting from changes in the duration of inundation due to upstream water projects. Vegetation type was determined in random plots along bars of the Gunnison River, Colorado. Elevation of plots was surveyed in relation to the river channel, and hydrologic models were used to predict how water projects might alter the number of plots in each inundation duration category. Inundation duration was assumed to be the single variable most strongly associated with vegetation pattern. While direct gradient analysis could prove useful for predicting the consequences of management actions, a difficulty is encountered if alterations to stream flow also change channel geometry. In this case, Auble et al. (1994) suggest that an additional step would be required to first predict the impact of the hydrologic change on the elevation and channel position of a representative number of plots.

Stromberg (1993) found that growing season flow volume could be related to indicators of riparian vegetation abundance, and that tree species richness varied with flood size. Models based on these relationships were suggested to be appropriate for roughly approximating the extent of riparian vegetation loss resulting from flow reductions.

Shafroth et al. (1998) modeled zones suitable for germination of riparian tree species in Arizona, by combining information on water surface levels from hydrologic models with observations of the timing of seed dispersal of riparian trees. This model is similar in concept to the "recruitment box" model developed by Mahoney and Rood (1998), although the parameters used to define zones suitable for germination differ. The recruitment box is the time interval of seed release of riparian tree species. If the rate of stage decline within this time interval is less than one inch per day, germination and initial establishment of riparian tree species is predicted to occur. Establishment over the long-term is additionally typically limited to a zone of two to seven feet in elevation above the late summer river stage. Seedlings germinating greater than seven feet above the low-flow stage are susceptible to drought induced mortality and seedlings (this value is based on maximum cottonwood root growth rates and capillary action in alluvial soils), and seedlings germinating at less than two feet above the low-flow stage are most susceptible to scour from future high flows.

Cieslik et al. (1993) provided an example of how models could be linked to address complex aquatic impact issues. As part of a comprehensive restoration planning effort along the Missouri River, a river and reservoir hydrologic model (Long Range Study (LRS) model) was used in conjunction with aerial photography to develop a stage vs. sandbar acreage relationship. Rules that describe hydrologic conditions that would result in sandbars becoming vegetated were developed from the literature (specific relationships used not described) and applied to hydrologic model simulations. The sum of predictions was used to determine how different water project alternatives would impact tern and plover nesting habitat on sandbars.

A summary and review of modeling approaches for different components of riparian systems is provided by Malanson (1993). According to Malanson (1993), models to predict vegetation response to hydrological alteration do not yet interactively incorporate geomorphologic variables such as changing deposition rates or erosion rates that have a substantial impact on vegetation pattern. This is an area where improvements to modeling approaches are needed.

A. POTENTIAL RIPARIAN AND WETLAND ZONES

The historical distribution of woody riparian vegetation versus freshwater marsh (wetlands) in the Sacramento-San Joaquin Rivers basin is reflected by topography and corresponding differences in soil texture. Woody riparian communities were found on the natural levees composed of silty, sandy sediments that extended some distances from the major streams, while marsh communities were found in more distant low-lying overflow basins dominated by fine-textured soils (Roberts et al. 1977, Thompson et al. 1977, Conrad et al.1977, Katibah 1984).

The composition of vegetation within the woody riparian zone is apparently regulated to a large extent by hydrologic processes and disturbance associated with flooding, rather than soil characteristics (Hupp and Osterkamp 1985, Osterkamp and Hupp 1984). Katibah (1984) noted that the historical extent of riparian vegetation in the Central Valley of California coincided approximately to the 100-year flood line. In semi-arid regions of the western U.S., vegetation pattern and zonation is likely also strongly impacted by patterns of water availability (maximum depth to groundwater, etc.) (Hupp and Osterkamp 1986). Hydrological alterations can have a dramatic impact on riparian vegetation, even if the mean annual flow stays the same, because vegetation is especially sensitive to changes in maximum and minimum river flows (Auble et al. 1994).

Holland's (1986) description of plant communities was used to delineate the five different vegetation zones likely to be encountered along Central Valley rivers. The Great Valley riparian willow scrub community (code 63410) (Zone 2) is located adjacent to the river channel, between the active channel habitats (Zone 1) and Great Valley cottonwood riparian forest (Holland code 61410) (Zone 3). This plant community is dominated by shrubby willows most resistant to flood disturbance (*S. exigua*) and seedlings and saplings of other willow species. The adjacent riverwash zone may become vegetated by herbaceous annual species during non-inundated periods or may remain unvegetated. The boundary between riverwash and willow scrub is determined by duration of inundation and intensity of scour (see Section A-5), while the boundary between riparian scrub and the taller cottonwood riparian forest is determined primarily by the frequency and intensity of scour (see Section A-4).

Great Valley cottonwood riparian forest (Holland code 61410) is found on alluvial soils close to perennial or near-perennial streams where groundwater is readily available, and is dominated by Fremont cottonwood (*Populus fremontii*) and Goodding's black willow (*Salix gooddingii*). Other more shade tolerant riparian tree species, such as box elder (*Acer negundo var californicum*) or Oregon ash (*Fraxinus latifolia*) may grow in the understory, but the frequency of flood disturbance generally does not allow these species to become part of the canopy. Without flood disturbance, willow scrub will transition into cottonwood riparian forest (Holland 1986, Holstein 1984, Jones & Stokes 1999).

Both Great Valley willow scrub and Great Valley cottonwood riparian forest types require the formation of barren sandbars (through flooding-caused scour and channel migration) for establishment, because seedlings grow best in full sun and do not compete well with other species. In addition, seed germination and seedling growth of these species requires specific hydrologic events (see Section A-3). Dependence upon water limits even mature plants to sites with readily available groundwater in the driest months of the year (see Section A-2).

On sites with less severe and less frequent flood disturbance (see Section A-4), Great Valley cottonwood riparian forest transitions into Great Valley mixed riparian forest (zone 4). Great Valley mixed riparian forest is generally found at a greater distance from the active river channel, where energy associated with flooding is less severe (Holland 1986). This vegetation type is also often found at slightly higher elevations above the active river channel, often due to the trapping of flood-borne sediments over time. This forest type contains the early-successional cottonwood (*Populus fremontii*) and willow (e.g. *Salix gooddingii*) species found in the Great Valley cottonwood riparian forest, in addition to box elder (*Acer negundo var. Californicum*), Oregon ash (*Fraxinus latifolia*), California black walnut (*Juglans californica var. hindsii*), and other more shade tolerant species. Valley oak (*Quercus lobata*) is also potentially an important species of the mixed riparian forest, especially on the highest elevation surfaces of the riparian zone located greater distances from the active river channel with the least severe flooding disturbance. (Note: in our definition of mixed riparian forest, we are grouping together the Great Valley mixed riparian forest (code 61420) and the Great Valley Valley Oak riparian forest (code 61430) distinguished by Holland (1986)). Holstein (1984) noted that mixed riparian forest transitions into sycamore (*Platanus racemosa*)-dominated woodlands on sites with deeper water tables and good soil aeration, but transitions into valley oak (*Quercus lobata*)-dominated woodlands on sites with deeper water tables and on sites with heavy clay soil and poor aeration. Without flood-caused disturbance, cottonwood riparian forest will become mixed riparian forest over time.

Freshwater marsh (code 52410) (Zone 5) is found in areas lacking significant current and not experiencing severe flood disturbance, where the establishment of trees and shrubs is limited by prolonged inundation. This vegetation type is dominated by cattails (*Typha* sp.), bulrushes (*Scirpus* sp.), and Sedges (*Carex* sp.). Areas with abundant freshwater marsh include the Sacramento- San Joaquin River Delta and edges of old river channels/ oxbow lakes. As previously noted, soils in these areas tend to be fine-grained (clayey soils).

A-1. Substrate Characteristics

Summary of Literature Review

As previously noted, in the prehistoric period, vegetation in the Sacramento-San Joaquin Rivers basin was distributed according to basin-floor topography and associated soil types. Woody riparian communities tended to be found on the higher, natural levees composed of silty, sandy sediments that extended some distances from the major streams, while tule marsh communities were found in more distant low-lying overflow basins dominated by fine-textured soils (Roberts et al. 1977, Thompson et al. 1977, Conrad et al. 1977, Katibah 1984). Within the natural levee areas, however, local occurences of coarser soils (i.e. sands and gravels), on the surface or in lenses at depth, can prevent the rooting of woody riparian species altogether (Griggs pers. comm.), resulting in cover by only annual herbaceous species.

Formulation of Recommended Relationships

Plants growing in these various environments are presumably adapted to the soil and moisture conditions that prevail in each. Tule marsh species (tules and cattails) require considerable shallow moisture and do not develop deep root systems, whereas woody riparian species can develop deep root systems through the more penetrable coarser-textured soils. This is not to say that wetland species cannot grow in coarser-textured saturated soils, and that woody riparian plants cannot grow in finer-textured soils. Nevertheless, growth rates and vigor of these plants would be expected to be superior where they are growing on soil types that constitute their natural habitat. For purposes of the ecosystem function model, it is important to gage whether actions to restore additional floodplain (e.g. relocating levees) will encompasses area of prime marsh habitat or prime woody riparian habitat. Thus, it is useful to make a simple assumption that areas of finer-textured soils will tend to provide prime marsh habitat, while areas of coarser soils will tend to provide prime woody riparian habitat. Of course, the requisite soil moisture conditions must also be present, as discussed in the following section.

A-2. Depth of Water Table

Summary of Literature Review

Cottonwoods and willows are very susceptible to drought stress (Tyree et al. 1994). In California, the lack of summer moisture limits riparian tree species to areas with readily available shallow groundwater. Riparian trees typically develop a network of roots extending to the edge of the groundwater zone or into the capillary fringe above the groundwater zone. Successful establishment of seedlings and saplings of cottonwoods and willows is also typically not possible without a high water table (see Secton A-3).

Stromberg et al. (1996) determined depth-to-groundwater ranges for various riparian species along the Upper San Pedro River in Arizona, in order to predict shifts in species composition in response to water table declines. Jones & Stokes surveyed elevations of various riparian species relative to the low-flow water surface along the American and Sacramento Rivers in California. The Nature Conservancy (Griggs) has considerable experience establishing new riparian forests along the Sacramento River at various elevations above the water table. In the table below are listed elevations above groundwater or low-flow water surfaces observed by these and other investigators.

Table A-1. Depth to Groundwater or Low-Flow Water Surface for Riparian Species

Species	Depth to groundwater	Location	Citation
Populus fremontii	≤ 10 feet	San Pedro River, AZ	Stromberg et al. 1996
	11 feet (trees), 1.5-5.0 feet (saplings)	Hassayampa River, AZ	Stromberg et al. 1991
	up to 26 feet	San Pedro River, AZ	Jackson et al. 1987 (cited in Stromberg et al 1991)
	≤ 21 feet [a]	Lower American River, CA	Jones & Stokes Associates 1998b
	≤ 20 feet	Sacramento River, CA	Griggs pers. comm.
	≤ 21 feet (most ≤ 16 feet)[a]	Sacramento River, CA	Jones & Stokes Associates 1977
Salix spp.	≤ 10 feet	Sacramento River, CA	Griggs pers. comm.
Salix lasiolepis	≤ 20 feet	Sacramento River, CA	Griggs pers. comm.
Salix gooddingii	≤ 10 feet (trees); (0-6.5 feet for seedlings)	San Pedro River, AZ	Stromberg et al. 1996
	11 feet (trees), 1.5-5.0 feet (saplings)	Hassayampa River, AZ	Stromberg et al. 1991
Fraxinus sp.	3.2-6.5 feet	San Pedro River, AZ	Stromberg et al. 1996
Juncus, Scirpus,	≤ 0.8 feet	San Pedro River, AZ	Stromberg et al. 1996

Typha, Eleocharis

Note:

[a] elevation above low-flow water surface elevation

Maximum elevation to groundwater may be somewhat greater along larger rivers than along smaller rivers (Mahoney and Rood 1998). This is at least in part due to the tendency for larger rivers to have more gradual stage changes, which is beneficial for germination and establishment (see Secton A-3), to have finer substrates for establishment (which hold moisture more readily), and to occur at lower elevations with longer growing seasons (Mahoney and Rood 1998).

Alterations in groundwater elevation can have substantial negative impacts to riparian tree communities. Scott et al. (1998) found that groundwater declines (due to in-channel sand and gravel mining) in a riparian system with formerly stable groundwater levels caused significant reductions in *Populus* growth and survival. Rapid declines of more than 3.3 feet resulted in the greatest negative impacts. In another study, Scott et al. (2000) determined that groundwater declines of more than than 3.3 to 5 feet, as a result of flood-related channel incision, resulted in high mortality and drought stress of cottonwoods along the Mojave River, CA. With more gradual declines, or declines of lesser magnitude, tree roots may be able to grow rapidly enough to follow the groundwater without significant negative impacts (Scott et al. 1998).

Riparian trees may be negatively impacted by rising water tables as well. Stromberg et al. (1997) documented an increase in riverine marsh habitat at the expense of riparian tree habitat, in response to decreased depth to the water table resulting from flood-caused channel modification.

Formulation of Recommended Relationships

Morphology of Groundwater Surface. In low-lying alluvial basins in non-arid environments, such as the Sacramento-San Joaquin Rivers basin, near-stream groundwater surfaces are expected to be relatively flat. We have not located any studies from the basin that depict the morphologly of the near-stream groundwater surface, however. Studies conducted by Jones & Stokes Associates in the Mono Basin revealed that the near-stream groundwater surface adjacent to a highly influent (losing) stream in very permeable substrate had a downward slope of only a few percent. In the Sacramento-San Joaquin Rivers basin, we would expect groundwater surfaces to typically slope upwards at very gradual slopes, on othe order of 0-1%. Of course significant local variations would be expected, especially in the vicinity of cemented Pleistocene sediments or shallowly-buried bedrock near the valley rim.

For application of the EFM, it would be desirable to excavate temporary test pits to measure groundwater depths in floodplains of a particular project reach. Test pits would be especially valuable in upper reaches of the tributary stream just below the major reservoir, since shallow bedrock is more likely to be present and topography is generally more complex. Where this is not feasible, we recommend adoption of an assumption that the groundwater surface during the growing season lies approximately at the average elevation of the low-flow water surface in the growing season. The average stage in August is the best measure of this elevation.

Maximum Depth to Groundwater Required to Support Riparian or Wetland Species. The observations summarized in Table 2-1 clearly point to a maximum depth of groundwater in the Sacramento River basin to support riparian species of approximately 20 feet. This is deeper than apparently observed in the more arid environments reported in the table, probably because of the factors identified by Mahoney and Rood, noted above.

Specific data regarding groundwater depth in freshwater marsh zones is limited to the data from Stromberg et al (1996) shown in Table 2-1. It is evident from field observaton that marsh communities must have standing water throughout most of the growing season, and at direct access to at least access to the zone of capillary rise above the water table at all times. A maximum depth of 1 foot is therefore a reasonable assumption, as it approximates the zone of capillary rise in coarser substates.

A-3. Flood Events Suitable for Plant Germination and Establishment

Summary of Literature Review

We describe the literature addressing this element below in separate sections for early and late successional species.

Early Successional Species - Cottonwood and Willow

Timing of Flow Peaks. Cottonwood and willow species in the western U.S. have evolved with natural hydrological cycles where peak flow typically occurs in the spring or early summer (Braatne et al. 1996). Seed of both species matures within six weeks of flowering in late winter and spring, and can germinate immediately upon being released (Braatne et al. 1996). Shafroth et al. (1998) reported that seed release for Fremont cottonwood on the Bill Williams River in Arizona was between mid-February and mid-April. Goodding's black willow trees on the same river released seed from late March to late June. Seed release for these two species in the Sacramento-San Joaquin River systems occurs somewhat later. Below are listed main seed release intervals for Fremont cottonwood, Goodding's black willow, and several other common riparian willow species growing in the Central Valley observed by a Jones & Stokes vegetation ecologist.

Table A-2. Seed Release Periods of Early Successional Riparian Species

Species	Seed Release Period	Year	Location
Populus fremontii	Mid Apr. - Late May	2000	San Joaquin R. (Knapp, pers. obs.)
	Late Apr. - Early Jun.	2000	Yuba R. tributary (Knapp, pers. obs.)
Salix gooddingii	Late May - Mid Aug.*	2000	San Joaquin R. (Knapp, pers. obs.)
Salix exigua	Early June - Early Sept.*	2000	San Joaquin R. (Knapp, pers. obs.)
Salix laevigata	Mid Apr. - Mid May	2000	Yuba R. tributary (Knapp, pers. obs.)
Salix lasiolepis	Mid Mar. - Early Apr.	2000	Yuba R. tributary (Knapp, pers. obs.)

Note:

* Seed release end-date estimated, based on observed flowering times.

For each willow or cottonwood species, the onset of the seed release period appears to be similar for trees growing along all major rivers of the Central Valley, with variation of one to two weeks possible (Knapp, personal observation). Much more variability in the timing of seed release appears to occur within populations, with some trees of the same species releasing seed much earlier than others. This explains the relatively broad range of seed release intervals for each species. The range given is for the main seed release period, where seeds and associated wind-dispersed pappus is readily visible in the air and on the surface of the water. Some smaller amount of seed may also be released outside of this main seed release interval. The window of seed dispersal may also differ among years, due to weather and other factors.

Successful recruitment depends on the appropriate river stage coinciding with natural seed dispersal of cottonwoods and willows. Seeds are commonly dispersed through the air or by water, and large numbers wash onto shorelines and bars as water levels recede. Seeds are extremely small and remain viable for only a few weeks after release (Moss 1938, Braatne et al. 1996). Once wet, viability is lost within days.

Rate of Hydrograph Decline. Mahoney and Rood (1998) developed a "recruitment box" model to describe hydrologic events that enable cottonwood seedlings to establish. The key element of this model is the assumption that seedlings growing at higher elevations along the river channel are prone to mortality due to desiccation, and seedlings growing at lower elevations along the river channel are prone to mortality caused by scour and disturbance from high river flows. Seedlings growing at intermediate elevations in the river channel potentially are more likely to escape both sources of mortality. Mahoney and Rood (1998) described this intermediate elevation as between 2-7 ft above the late summer stream stage, but these elevations vary with the river system, and successful recruitment appears to occur at higher elevations along larger rivers. A critical element identified by the investigators is the rate of river stage decline following peak flows. Rate of decline of greater than one inch day were considered to potentially increase seedling mortality, because root growth of willows and cottonwoods may not be able to keep pace with the lowering water table (Mahoney and Rood 1998).

Under natural flows, the hydrograph of most rivers (especially regulated rivers with upstream inpoundments for water supply) typically initially declines rapidly following peak flows (>> 1 inch reduction in stage per day), and then declines slower thereafter. If this time during which river stage is receding less than the maxiumum rate of root growth coincides with tree seed release and is high enough on the river bank to fall within the elevation of the "recruitment box", successful recruitment may result. The particular parameters described by Mahoney and Rood were validated experimentally through manipulation of flow recession after a flood on the Oldman River in Alberta, Canada (Rood et al. 1998).

Seedling survival with somewhat faster rates of decline have been documented: up to 1.65-1.75 inches per day (Shafroth et al. 1998). Segelquist et al. (1993) found 47% survival of seedlings with a drawdown of 1.15 inches per day. Along the Sacramento River, researchers from The Nature Conservancy found that a planted Fremont cottonwood cutting grew roots 16 feet deep in a little more than one growing season, equivalent to a sustained root growth rate of about 1.5 inches per day; they believe that growth rates are dependent upon the particular texture of the sequence of sediments in the soil profile (Griggs pers. comm.). Researchers on riparian habitats along the San Joaquin River (Scott pers.comm.) suggest that a maximum rate of stage decline of 2–4 cm per day (0.8–1.6 inches per day) would be sufficient to allow riparian plant establishment. In general, however, few cottonwood seedlings are expected to survive if rates of stage decline are much greater than 1.5 inches per day (Mahoney and Rood 1991). Roots of cottonwoods and willows may not need to grow roots fast enough to keep up with these higher rates of flow recession (Fenner et al. 1984, Reichenbacher 1984, references cited in Braatne et al. 1996), because the capillary fringe above the receding water table may enable seedlings to avoid desiccation even when the rate of flow recession exceeds the rate of root growth. Most of the available root growth rate data is for cottonwood; willows may or may not have similar root growth rates.

Based on the foregoing, models developed for recruitment might differentiate between rates of stage decline with different probabilities for successful recruitment:

Table A-3. Generalized Relationship between Rate of Water Table Decline and Seedling Survival

Rate of Water Table Decline (inches/ day)	Riparian Tree Seedling Survival
< 1	Good
1 to 1.5	Fair
> 1.5	Poor

It should be noted that mature cottonwood and willow trees are frequently found at higher river channel elevations than where recruitment typically occurs. This is due to the sediment trapping action of vegetation and causing vertical accretion of the floodplain (Auble and Scott 1998).

Numerous seedlings frequently germinate in low-flow years, but usually only occur in a narrow band adjacent to the low-flow channel. These seedlings are typically lost due to scour at future higher flows (Howe and Knopf 1991, Auble and Scott 1998, Rood et al. 1998). (See Section 5, below).

Rood et al. (1998) suggested that reservoir release regimes negatively impact cottonwood and willow establishment on many rivers. Changes in flows released downstream from dams are often rapid, which may desiccate seedlings when stage declines too rapidly or can wash seed away or seedlings. Strahan (1984) suggested that reduced germination success of riparian trees along the Sacramento River may be due to higher flows following low flows that occurred during the main seed release period, effectively washing away many of the seeds deposited in areas otherwise suitable for germination.

Shafroth et al. (1998) modeled areas suitable for germination as between the highest and lowest river stage during the seed release period for a species. Within this potential germination zone, the basal area of existing mature woody vegetation, the maximum annual depth to groundwater, and the maximum rate of groundwater decline were variables that best discriminated between areas with and without actual seedling recruitment. Shafroth et al. (1998) suggested that elevation above summer base flow may be superior to rate of stage decline for predicting seedling survival, as this variable integrates two causes of seedling mortality: removal by scour from high flows, and desiccation due to deep water tables.

In addition to dependence on specific hydrologic events in the season of germination, lack of large floods for several years after a germination event is also generally a requirement for long-term establishment (Stromberg et al. 1991). Seedlings and saplings are very vulnerable to flood-caused scour and disturbance. Reductions in flood-caused disturbance, which is often a byproduct of upstream dams, can cause riparian tree seedlings to establish in formerly inhospitable parts of the river channel (Friedman and Auble 1999). Encroachment of riparian vegetation may not be desirable due to concerns about channel conveyance.

Frequency. The hydrological requirements for widespread germination events of many cottonwood and willow species are not met in each year. In some years, the period of overbank flows does not coincide with the period of seed release for cottonwoods and willows or rates of hydrograph recession may be tooo rapid. Historical records and tree aging studies have shown that in numerous riverine environments in the Western U.S., the combination of factors leading to a large-scale recruitment event typically occurs once every 5-10 years (Mahoney and Rood 1998, Scott et al. 1997, Stromberg et al. 1991). Scott et al. (1997) determined that recruitment of mature cottonwoods on the upper Missouri River in an area with little channel movement was most likely on surfaces inundated by floods with a recurrence interval of more than nine years. Hughes (1994) (cited in Scott et al. 1997) wrote that long-term cottonwood establishment was associated with even longer flood return intervals (30-50 years) along some non-meandering rivers.

Along meandering rivers, channel migration leads to the formation of new exposed bars optimal for cottonwood and willow regeneration, even in the absence of flood flows. Whatever the means by which bars colonized by cottonwoods and willows were formed, without flood disturbance, natural succession will result in cottonwood riparian forest becoming mixed riparian forest over time (Strahan 1984). The greater the time interval since the last major disturbance (and the last major recruitment event), the greater the proportion of riparian forest habitat that will be composed of mixed riparian forest. The time required from germination of the cottonwood riparian forest until succession to the mixed riparian forest type is not well documented. Brice 1977 (cited in Strahan 1984) reported the maximum age of riverside forests along the Sacramento River composed of cottonwoods and tree willows to be 73 years of age. The time for this transition has also been predicted to be approximately 30-50 years (Kroemer date unknown).

Late Successional Species - Box Elder, Oregon Ash, Sycamore, Valley Oak

Seedlings of late-successional riparian tree species are more tolerant of shade than willows and cottonwoods, and establishment of these species is therefore typically not dependent on flooding events to create bare sandbars. In addition, seedling germination and establishment in these species is not as closely dependent on specific hydrologic events during and immediately following the seed release period as it is for willows and cottonwoods.

Seeds of the late successional riparian species that dominate the mixed riparian forest mature are released in the fall and winter (Table A-4).

Table A-4. Seed Release Periods of Late Successional Riparian Species

Species	Seed Release Period	Location
Platanus sp.	October - April	Burro Cr., AZ (Asplund and Gooch 1988)
Platanus wrightii	Fall/ Winter	Arizona (Bock and Bock 1989)
Juglans sp.	September -October	Burro Cr., AZ (Asplund and Gooch 1988)
Fraxinus sp.	September - October	Burro Cr., AZ (Asplund and Gooch 1988)

These seeds may be transported and redeposited by high winter and spring river flows. Germination typically occurs earlier in the season than for willows and cottonwoods, when moisture from rainfall is more readily available. In addition, seeds of these species often requires burial, and partially shaded environments favor seedling germination and survival (Asplund and Gooch 1988). These late-successional species are thought to be less resistant to flood disturbance caused mortality than the early successional cottonwoods and willows.

Formulation of Recommended Relationships

Adopting fixed minimum and maximum elevations above the low-flow water surface elevation for germination and successful establishment of seedlings, such as reported by Mahoney and Rood (1998), does not appear justified. As they noted, values used would be expected to vary between river systems, and is appears that their particular values (2 feet to 7 feet) are inappropriate for the Sacramento and San Joaquin River systems. Root growth of 1.5 inches per day, as has been observed, implies that successful establishment may occur 15 feet or more above the later summer stage. In addition to adopting the obvious seasonality requirement, it seems logical to rely on an assumued maximum root growth rate alone, and to not further constrain successful establishment to an arbirary maximum elevation. Likewise, establishing an arbitray lower elevational limit is not logical. The lower limit, established by scour and inundation, is addressed in Section 5, below.

Besides the rate of point bar formation resulting from channel migration and allowing riparian cottonwood and willow recruitment (see Section B-1), the frequency of overbank flows suitable for willow and cottonwood seedling recruitment will determine the relative proportions of riparian habitat occupied by cottonwood riparian forest and mixed riparian forest. Actions that cause the average interval between suitable germination and establishment years to increase will lead to an eventual decrease in the proportion of early successional cottonwood riparian forest. The proportion of mixed riparian forest proportion will approach 100% if the interval between suitable large-scale germination and establishment events exceeds the average life-span of the cottonwood riparian forest (approximately 50 years). The boundary between the cottonwood riparian forest zone (Zones 3) and the mixed riparian forest zone (Zone 4) may in fact be a transition zone with gradients of species occurences. A reasonable approimation of the midpoints of this gradation would therefore be where the frequency of suitable recruitment events has a return period of approximately 50 years.

A-4. Scour Regime of Riparian Zones

Summary of Literature Review

Flood disturbance and scour is a major factor limiting the spatial extent of riparian tree vegetation along rivers. Friedman and Auble (1999) give several ways by which scour causes mortality of riparian trees: abrasion by debris may cause bark damage that leads to mortality, debris piles may cause hydraulic drag on trees resulting in damage or death, shear stress may be high enough to mobilize the sediment in which trees are rooted and wash the trees away, sediment deposits may kill trees, and bank failure following erosion of sediment at the base of the bank may remove riparian trees.

Frequent scouring flows may cause areas adjacent to the summer low flow channel in western rivers to be devoid of woody vegetation, instead exhibiting large gravel and sand bars with sparse herbaceous vegetation (Peltzman 1973, Kondolf and Wilcock 1996). Long-term establishment of trees at the edge of low-flow channels can occur in heavily modified rivers, where flow is stabilized at low levels for many years without scouring floods (Shafroth et al. 1998). The dramatic increase in near-channel woody vegetation established downstream along the San Joaquin River after the construction of Friant Dam is an example (Cain 1997, Jones & Stokes Associates 1998).

Establishment of trees at low elevations in the river channel may cause channel narrowing and conveyance problems, and scouring disturbance associated with flood flows may be important for maintaining existing vegetation patterns. Scouring flows are also necessary to create the bare moist sandy bars on which cottonwoods and willows establish. Cottonwood and willow seedlings are poor competitors and do not grow well in the presence of other vegetation and less-than-full sunlight (Braatne et al. 1996, Stromberg et al. 1991).

Scour disturbance interrupts the riparian ecological succession sequence. The typical ecological succession sequence proceeds from unvegetated bars (riverwash) to riparian scrub, then to cottonwood riparian forest, and ultimately to mature mixed riparian forest. Frequent scour may prevent the establishment of woody riparian vegetation by removing seedlings and saplings, and may cause sand- and gravel bars to remain unvegetated. Seedlings and saplings may also be removed by prolonged inundation (see Section A-5, below). Floods that are frequent enough to prevent scrub from developing into forest determine the elevation of the boundary between the potential riparian scrub and cottonwood riparian forest zones. Less frequent but much larger floods remove mature willow and cottonwood trees and prevent the development of mature riparian forest. These flows determine the elevation of the boundary between cottonwood riparian forest and mixed riparian forest.

Formulation of Recommended Relationships

The relative magnitude and frequency of floods, and the natural development rate of riparian vegetation (i.e., succession rates including establishment), determines the long term average boundaries between the potential riparian zones. The elevations at which scour occurs are determined by a number of local conditions, including the age and structure of riparian vegetation, substrate size and cohesion, floodway morphology, and stream gradient.

The long term average boundaries between the riparian scrub and cottonwood riparian forest zones (Zones 2/3) and between the cottonwood riparian forest and mixed riparian forest zones (Zones 3/4) will respond to changes in the shear stress regime during overbank flooding. The shear stress regime is affected by changed in the frequency of particular flows, most directly by changes in depth of those flows. (That is, on wide rivers, shear stress is proportional to the product of slope and flow depth.). Accordingly, two approaches to simulating effects of changes in flow regime should be explored at the application level.

First, changes in scour potential and average locations of boundaries of these riparian zones can be approximated by comparing the distribution of flow depths over the floodplain for with-project and without-project flows having the same return period. The pattern of flow depth for the without-project condition for a particular overbank flow (e.g., a 5-year or 10-year return period flow) can be assumed to control the existing Zones 2/3 and 3/4 boundaries. Changes in the pattern of flow depth for the with-project flow having the same return period can be used to predict the change in the location of the these two zone boundaries.

Second, using a surrogate for scour effects, changes in average locations of the boundaries can be approximated by changes in area of inundated floodplain for with-project and without-project flows having the same return period. The return periods of the without-project flows corresponding to the existing locations of the two zones boundaries are determined, and the stages of the with-project flows having the same return periods define the locations of the with-project boundaries.

The first approach may be preferable, in that it directly relates changes in zone locations to changes in flow depth, and therefore changes in shear stress. The second approach may be useful as well, however, it that it relates changes in zone locations to changes in the frequency of overbank flows.

A-5. Scour and Inundation of Active-Channel Habitats

Summary of Literature Review

The lowest extent (elevation) of woody riparian vegetation near the river channel is a function of tolerance to scour (Section A-4 above) and tolerance to inundation. Extended periods of inundation during the growing season causes anoxia in the root zone, interference with leaf transpiration, or depletion of energy reserves. Many factors determine the duration of inundation that plants can survive, including temperature, depth and velocity of the water; timing of the inundation relative to the growing season; species, age, size, and gender of the plant (Whitlow and Harris 1979, Kozlowski 1984, Friedman and Auble 1999).

Even flood tolerant tree species may suffer if inundated for long periods of time, particularly during the growing season. Spink and Rogers (1996) found high rates of mortality for *Salix nigra* and *Acer saccharinum* trees in response to a flood of exceptional duration that occurred along the Mississippi River in the summer of 1993. Bases of trees remained inundated from July through October. Mortality was especially pronounced for saplings. Flooding that lasts longer than 40% of the growing season is generally thought to prevent colonization by woody plants (Gill 1970, Toner and Keddy 1997). In the Sacramento/ San Joaquin River systems, 40 % of the growing season would represent approximately 85 days. Longer duration of inundation would possibly be necessary to kill existing mature trees. However, small seedlings having their low canopy entirely inundated were found to suffer leaf loss after 3 weeks inundation in the fluctuating inundation zone of Lake Isabella in California (McCarten per. comm.).

Friedman and Auble (1999) investigated the relative importance of inundation and scour induced mortality on box elder removal from a canyon reach of the Gunnison River. They developed an empirical model to determine what percentage of the canyon bottom vegetation would be removed by combinations of peak discharges that mobilize sediment and discharge exceeded for 85 days during the growing season.

Formulation of Recommended Relationships

The elevation of the lower boundary of the potential riparian scrub zone should be determined by considering both scour and inundation. Both factors affecting the lower boundary of the potential scrub zone -- the one resulting from scour mortality (by inundation during higher flows) and the one resulting from growing-season inundation mortality (by inundation during low flows) should be modeled for the without- and with-project conditions. The factor that causes the highest lower potential scrub zone boundary should be assumed to be the determining factor for the boundary.

Changes in the riverwash zone due to scour-induced mortality can be estimated by a analogous method to those two options described in Section 4 above for changes in riparian zone boundaries. Inundation-induced mortality can be determined by examining without-project and with project flows during the low-flow season, by assuming that mortality to seedlings attempting to establish near the low-flow channel will occur if the vegetation is inundated for at 21 days during this period.

B.

RATES OF ECOSYSTEM CHANGE

B-1. Rates of Channel Migration

Summary of Literature Review

Channel migration in an alluvial river is controlled by the dynamics of flow against channel bed and banks. This involves the application of high velocity or high shear stresses, usually against the outer bed and bank of a meander bend. The rate of bank erosion and channel migration is a function of the balance between the erosive force of the helical flow against the channel bank and the resistance and structure of the outer bank. The most successful predictive tools to date for determining migration rate have focused on channel geometry (usually the ratio of radius of curvature to width). However, a few studies have focused on using discharge (or surrogates such as drainage area) to predict channel migration rate.

In almost all such studies, discharge has been positively correlated with channel migration or bank erosion rate (Hooke, 1979; Hagerty et. al, 1983; Hasegawa, 1989). However, no equations have been developed to date which relate a specific discharge to a specific migration rate. Instead, general relationships have been identified. The study of hydraulic geometry (Leopold and Maddock, 1953; Leopold et al. 1964) has focused attention on now well-known relationships between discharge and channel geometry (channel width, depth, slope, wavelength). Schumm (1977) was the first to identify overall relationships between changing discharge and channel form. He observed that increasing discharge increased channel wavelength, while increasing sediment load increased wavelength while decreasing sinuosity (with the obvious inverse relationships). These relationships imply that increasing discharge will change channel form to reach a new equilibrium value, but channel change will only occur until a new equilibrium form is found (Hicken, 1977; Hooke, 1984).

A direct relationship has been found between channel migration rate and increased discharge (or increased velocity due to increased discharge) for the Ohio River (Hagerty et. al 1983), the Beaton River in Canada (Nanson and Hicken 1986), the River Avon in the U.K. (Maddy et al1999), and the Burhi-Gandak in India (Philip and Gupta 1993). Some of the best studies have come from diversion structures and dams on individual rivers. Bradley and Smith (1984) found a diversion into the Milk River (that increased discharge) caused meander migration to increase from 1.35 to 2.2 m/yr over a 65 year period, while a downstream dam on the same river (that decreased discharge) caused a decrease in migration rate from 1.75 to 0.45 m/yr over a 75 year period. Friedman et al (1998) found in a study of 35 dam sites that the primary response of a downstream meandering channel to the decrease in peak discharge and sediment load caused by dam building was a decrease in meander migration rate.

However, the measure of discharge that best correlates with changing migration rate is not clear, and is often not mentioned in these studies. Sometimes, the flows are simply described as peak flows or moderate floods (Hooke, 1979; Blacknell, 1982; Whitlow and Gregory, 1989). Pizzuto (1994) found that at a discharge greater than $Q_{2.7}$, erosion exceeded deposition on the Powder River, and the channel expanded. Arnold et al. (1982) found that increasing bankfull discharge and increasing frequency of moderate floods caused channel widening and bank erosion. Erskine (1995) had a similar finding, that bankfull or higher, prolonged releases below a dam on the Wingecarribee River had the greatest morphologic impact. Nanson and Hicken (1986) found that the Q_5 (five-year flood) accounted for 34% of the variance in migration rate for 18 channels in western Canada. Finally, Daniel (1971) showed that path length for an individual meander shows a strong direct relationship (for individual channels) to the cumulative total flow volumes for days above average channel discharge. This points to a possible consensus of channel modifying flows that occur around bankfull and higher. However, bank erosion has also been related to lower, average discharges (Cherry et al 1996; Chang and Toebes 1980), declining flows (Thorne and Tovey 1981), or rapidly fluctuating flows (Budhu and Gobin 1995).

On the Sacramento River, flow impoundment at Shasta Reservoir caused a major change in flow regime, but Harvey was not been able to determine any changes in erosion rates (lateral migration) between the pre- and post-Shasta Dam periods (Harvey pers. comm.). Clearly moderate-large floodflows have been reduced and low flows augmented; however, changes to the $Q_{1.5}$ to Q_5 flows may have been much less.

Formulation of Recommended Relationships

Rates of channel migration vary by river reach in the Sacramento-San Joaquin Rivers system, due to the distribution of bedrock and resistant Pleistocene formations, tectonic factors, and the reach's flow regime. In reaches having little or no tendency to meander or migrate, changes in flow regime will have relatively little effect on rates of channel migration. Table A-5 indicates those reaches where channel migration is significant. In this regard, it should be noted that existing bank protection in some reaches may inhibit or prevent channel migration in reaches where a tendency to channel migration is still present. Some measures may involve the removal of such bank protection, and in such reaches channel migration presumably would be reinitiated.

In reaches subject to channel migration, the river's response to changes in flow will be to migrate more if flows of certain frequency increase, or to migrate less if these flows decrease. According to the foregoing discussion, the best indicator of this effect will be changes in the smaller floodflows, i.e. flows having return periods from about 1.5 years to about 5 years. It can be assumed that increases in these parameters will increases rates of migration, and visa versa, but it is not possible to establish a predictive function between change in these flows in cubic feet per second and changes in migration rates in feet per year. Only the direction of change can be ascertained.

Increases in rates of channel migration may be beneficial or detrimental to ecosystem functions. If existing rates are near or exceed rates at which early successional stages succeed to later successional stages, further increases will be detrimental because the system will be unable to develop the full diversity of vegetation communities inherent in the presence of the later successional stages.

In most cases in this system, however, existing rates of channel migration have been suppressed by bank protection and floodway narrowing and deepening. The "recycling" of older vegetation communities to earlier successional stage has been slowed, and increases in channel migration will therefore tend to benefit the ecosystem.

C. CONNECTIVITY TO AQUATIC HABITATS

The degree of connection of riparian habitats to aquatic habitats in terms of periodic allochthonous inputs and providing seasonal fish rearing habitats depends upon the extent, timing, depth, duration, rate of recession, and frequency of overbank flows. These variables also govern the availability and suitability of seasonal wetlands for wildlife. The former is addressed in "Section 3. Aquatic Ecosystem Model", Section II, element C, and in the corresponding sections of Appendix B. Development of the latter has been deferred.

Table A-5. Reach Delineation for Sacramento and San Joaquin Rivers and Major Tributaries

River/Reach	River Miles	Characteristics
Sacramento River	243-0	4 Reaches
Red Bluff-Woodson Bridge	243-200	coarse grained, cobble bed, meandering, moderate sinuosity, constrained laterally by Pleistocene terraces
Woodson Bridge-Colusa	200-143	coarse grained, gravel bed, meandering, moderate sinuosity, constrained by Modesto o/crop on west and Butte Basin on the east, well developed natural levees
Colusa-Walnut Grove	143-48	fine grained, sand bed meandering, high sinuosity, bounded by flood basins (Colusa, Sutter, American, Yolo)
Sloughs and Distributary Channels	48-0	sand bed, very fine graind banks, low rates of lateral migration, probably avulsion driven, tidal and wave effects
San Joaquin River	267-54	7 Reaches
Friant - Gravelly Ford	267-229	coarse grained, terrace confined, low sinuosity, meandering channel, severely impacted by sand and gravel mining; (Q_{bf} = 8,000 cfs)
Gravelly Ford - Mendota	229-205	fine grained, levee confined, moderate-high sinuosity, meandering channel, sand bed, modern alluvial fan of San Joaquin River; (Q_{bf} = 2500 cfs)
Mendota - Sack Dam	205-182	fine grained, sand bed, moderately sinuous meandering channel confined by low terrace on the west and the toes of the coalesced alluvial fans on the east
Sack Dam- Merced River	182-118	Anabranched/anastomosed multiple channels inset below resistant Pleistocene age terraces, forming discrete parallel flow paths, sand bed
Merced River - Tuolumne River	118-83.8	fine grained, moderately sinuous, meandering channel, probably degrading, sand bed, 30 % eroding banks (Q_{bf} = 10,000 cfs)
Tuloumne River - Stanislaus River	83.8-74.8	fine grained, moderately sinuous, meandering channel, 20% eroding banks, split flow reaches (Laird Slough, Finnegan Slough), sand bed; Q_{bf} = 15,000 cfs)
Stanislaus River-Old River	74.8-54	fine grained, high sinuosity, meandering channel, 19% eroding banks, levee confined, sand bed; (Q_{bf} = 20,000 cfs)

River/Reach	River Miles	Characteristics
American River	23 -0	5 Reaches
Nimbus Dam-RM 17	23-17	very coarse cobble-boulder bed material, low sinuosity channel, confined by erosion resistant Pleistocene age terraces
RM 17- Goethe Park	17 -11.5	coarse grained, cobble and gravel bars as veneers over Pleistocene outcrop, laterally confined by terraces
Goethe Park - RM 8	11.5-8	coarse grained, gravel bed with Modesto outcrop in bed, split flow reaches
RM 8- RM 4.8	8-4.8	coarse grained, moderately sinuous, meandering, heavily revetted, incised reach
RM 4.8 - Sacramento R. Confluence	4.8- 0	fine grained, sand bed, low sinuosity, incised
Feather River	61-0	5 Reaches
Oroville Dam-RM 54	61-54	coarse grained, cobble bed, straight, confined by gold dredge tailings
RM 54- RM 45	54-45	coarse grained, cobble bed, low sinuosity, split flow, with high sediment supply from erosion of dredge spoils upstream
RM 45 - Yuba River Confluence	45-28	coarse tofine grained, moderately sinuous meandering channel, extensive bank erosion
Yuba River-Bear River	28-11	fine grained, low sinuosity meandering channel, Modesto o/crop in banks and bed (RM 24), alternate bars, probably still incising into HMD
Bear River-Sacramento River	11-0	fine grained, low sinuosity straight channel, leveed on east side, Sutter Bypass on west side, low bank erosion at moment, but could increase in future as channel deepens --stability depends on continued supply of sediment from Bear and Yuba Rivers
Yuba River	24-0	5 Reaches
Englebright Dam-Parks Bar	24-20	bedrock canyon
Parks Bar - d/s end of dredge spoils	20-8	coarse grained, braided, straight channel, bounded by dredge spoils, aggraded above Daguerre Point Dam, degrading(?) below dam
Dredge Spoils-RM 5	8-5	coarse grained, gravel-cobble bed, incised below HMD terraces, braided low- water channel
RM 5 - RM 2	5-2	incised into and confined by Riverbank Fm outcrop, probably degrading, active bank failures
RM 2-RM 0	2-0	fine to coarse grained, extensive sediment storage in low relief bars (backwater from Feather River), leveed

River/Reach	River Miles	Characteristics
Stanislaus River	35-0	3 Reaches
Knights Ferry - H/Way 120	35-25	coarse grained, cobble bed, terrace confined, placer and dredge mined
H/Way 120 - Head of Levees	25-5	coarse grained, active meandering channel confined by terraces
Head of Levees - San Joaquin River Confluence	5-0	fine grained, sand bed, actively meandering, revetted, floodplain bounded by levees (Q_{bf} = 5,450 cfs)
Tuolumne River	40-0	4 Reaches
La Grange - Roberts Ferry	40-28	coarse grained cobble-gravel bed, dredge mined, sand and gravel mined
Roberts Ferry - J14 Bridge	28-18	coarse grained, gravel bed, narrow floodplain confined by terraces, heavily sand and gravel mined
J14 Bridge - Shiloh Road	18-4	fine grained, sand bed, meandering with narrow floodplain confined by terraces
Shiloh Road - San Joaquin River confluence	4-0	fine grained, unconfined meandering river with wide floodplain, levees and revetments (Q_{bf} = 5,200 cfs)
Merced River	38-0	4 Reaches
Merced Falls - Snelling Road	38-30	coarse grained, cobble bed, some outcrop in bed, dredge spoils
Snelling Road - Shaffer Bridge	30- 23	coarse grained, gravel bed, severely affected by sand and gravel mining, floodplain is wide
Shaffer Bridge - River Road Bridge	23-3	fine grained, sand bed, narrow floodplain confined by terraces, meandering channel with actively eroding banks
River Road - San Joaquin River Confluence	3-0	fine grained, sand bed meandering channel, floodplain with levees, active bank erosion (Q_{bf} = 6,000 cfs)

Notes:

Q_{bf} = bankfull discharge
RM = River Mile

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APPENDIX B. DERIVATION OF RELATIONSHIPS RECOMMENDED FOR THE AQUATIC ECOSYSTEM MODEL ELEMENT

This appendix of the aquatic ecosystem model consists of two parts:

- a review of existing models potentially applicable to the Sacramento–San Joaquin River system, and
- a literature review and a description of the rationale for each of the recommended physical-biological relationships for the aquatic ecosystem model element.

REVIEW OF EXISTING MODELS

Existing models that could be applied to depict how flood damage reduction actions could be implemented to maintain and enhance the aquatic ecosystem include habitat-, population-, and ecosystem-level models. Habitat models generally incorporate suitability indices for chinook salmon in a habitat evaluation procedure developed by the U.S. Fish and Wildlife Service. Population models have been developed for chinook salmon and specifically for rivers in the Sacramento–San Joaquin system. Population models typically integrate equations for growth, survival, movement, and reproduction as a function of environmental conditions. Ecosystem level models are more general and have been developed for the Sacramento–San Joaquin system and other aquatic ecosystems. Ecosystem models generally assume that restoration, reestablishment, and maintenance of ecosystem processes and structure will restore and maintain habitats needed to support biological communities and species populations. Many of the relationships identified for the Corps' ecosystem functions model (EFM) are based on relationships similar to those included in the models discussed below.

Habitat Models

Habitat Suitability Index models combine multiple physical habitat relationships for fish species (U.S. Fish and Wildlife Service 1982). Physical habitat includes the resources and conditions present in an area that indicate the acceptable environmental conditions relative to spawning, rearing, and movement of each fish species. Habitat Suitability Index models condense information on physical habitat requirements into a set of habitat evaluation criteria, structured to produce an index of overall habitat quality. Application of the criteria requires consideration of fish needs in conjunction with existing environmental conditions and study objectives. Species habitat relationships are available for chinook salmon that are based on existing habitat suitability indices (Raleigh et al. 1986).

The physical habitat simulation model is commonly used in combination with instream flow incremental methodology for habitat modeling related to instream flow variability (Milhous et al. 1989, Bovee 1982). Physical habitat simulation may incorporate Habitat Suitability Index relationships or habitat-physical processes relationships developed for specific locations and species populations. Generally, water depth, velocity, and substrate are the primary variables used in the physical habitat simulation model to represent habitat. The assumption is that physical habitat, represented by depth, velocity and substrate, is the limiting factor to fish abundance. The assumption, however, has not been well substantiated and detailed understanding of local biological conditions is required to predict expected population responses to changes in habitat elements.

Milhous (1998) discusses an instream flow model relating instream flows and substrate size to species needs. The model has three components: biological, hydraulic, and selection. The biological component identifies the substrate size needed by a species and the management objectives for the stream. The hydraulic component assesses the flow required to maintain the channel morphology needed for the species of interest, including hydraulic requirements for removal and transport of unwanted sediment. The selection component determines the magnitude, duration, and frequency of flows needed to manage sediment movement through the river. The model can simulate removal of fines and sand from riffles, maintenance flows, removal of fines and sand from river as a whole, removal of gravels from pools, and scour of side channels. The model provides limited information on flows needed to maintain riparian vegetation and sediment movement outside of the stream channel.

Population Models

A number of population models have been developed for chinook salmon in the Sacramento River (Kimmerer et al. 1989, Bartholow et al. 1993, Kent 1999, Kimmerer and Jones & Stokes Associates 1999). The main purpose of these population models is to provide a tool to evaluate management strategies. All of the models discussed below simulate all life stages of the fall-run chinook salmon, and the individual-based model allows simulation of four chinook salmon races and interactions between them (Kimmerer and Jones & Stokes Associates 1999). Life history events include ocean rearing, migration and spawning of adults, in-gravel egg incubation, and rearing and movement of juveniles. Time steps range from daily to weekly and simulations may encompass a few months to several years. The models are comprised of equations that relate individual responses (i.e., survival, growth, and movement) to environmental conditions (i.e., water temperature, metals concentrations, etc.).

The Chinook Salmon Population Model (CPOP2) simulates the population dynamics of the fall-run chinook salmon in the Sacramento River system (Kimmerer et al. 1989). The CPOP2 model consists of four sub-models that represent the main chinook life stages: ocean, upstream migration, spawning, and downstream migration. Model simulation starts and ends with smolts entering the ocean from the estuary. The model input includes historical hydrology, temperature, and metal concentration data. The main purpose of simulations is to estimate the effects of changes of flow timing and magnitude in the Sacramento River on the abundance of fall-run chinook salmon.

Another model that simulates chinook salmon population dynamics is the San Joaquin River System Chinook Salmon Population Model (EACH) (EA Engineering, Science, and Technology 1991). The EACH model is a mechanistic model that simulates populations of three San Joaquin River tributaries upstream of the Sacramento–San Joaquin Delta: the Stanislaus, Tuolumne and Merced Rivers. The main purpose of this model is to identify key factors determining the production of chinook salmon in the San Joaquin system, characterize pathways and interactions of the key factors, and evaluate their importance. Like other models, EACH is also composed of four sub-models that represent different life history events: ocean rearing, tributary spawning, tributary rearing, and Delta/Bay movement and rearing.

SALMOD was originally developed for the Trinity River by the U.S. Fish and Wildlife Service (Williamson et al. 1993) and was later applied to the Sacramento River fall-run chinook salmon (Kent 1999). The SALMOD model assumes that egg and fish mortality are linked to flow-related habitat variability and that water quality, including dissolved oxygen, suspended sediment, and nutrient loading, does not limit the fish population. Fish standing crop can be estimated from data on physical habitat, food production, and water temperature. Fry, pre-smolt juveniles, and spawning adult abundance is constrained by physical habitat, food abundance, physiological requirements, reproduction requirements, behavioral factors (i.e. crowding stress), and cover availability. Physical habitat abundance is related to flow for fry and juveniles and gravel quality for adult spawning and egg incubation. SALMOD has important water management implications, but calibration and accuracy depend on abundance estimates for out-migrating juveniles (Kent 1999).

The Sacramento River Chinook Salmon Individual-Based Model (Kimmerer and Jones & Stokes Associates 1999) keeps track of individual fish and accounts for spatial and temporal heterogeneity. The additional flexibility of individual-based models potentially provides an improved representation of the population response to environmental variability. Like other models, the individual based model is designed in modules that correspond to chinook salmon life history events. Model parameters include single values that describe the shape of functions, spatial structure, intrinsic characteristics of the fish, and model operations controls. Annual parameters include hatchery release schedules and fishing effort. Environmental conditions can be modified by the user to simulate the response of specific life stages and the population. Environmental data consists of historical or simulated water temperature, river flow, diversion volume, substrate condition, pollutant concentration, and dam and diversion gate positions.

Ecosystem Models

The Community-Based Habitat Suitability Index model identifies key habitat components for shaded riverine aquatic (SRA) cover in selected reaches of the Sacramento River System. Like the habitat suitability index (HSI) models, this community-based HSI model integrates information on physical habitat requirements into an index of overall ecosystem quality. Its primary purpose is to provide a means to assess biological community impacts for streambank protection projects in the Sacramento River System. The model is designed to represent physical requirements for several native, regionally important fish and wildlife species, including anadromous salmonids, belted kingfisher, wood duck, great blue heron, semiaquatic mammals, and amphibian and reptile species.

The model defines the SRA cover as "the unique, nearshore aquatic area occurring at the interface between a river and adjacent woody riparian habitat"(Fris and DeHaven 1993). Cover, depth, and substrate composition are the main components that constitute SRA cover. SRA cover is further described by overhanging cover, in-water cover, overhead cover, and instream cover interaction.

The ecosystem level model developed by Levy et al. (1996) identifies indicators of ecological integrity at three levels of ecological organization: the landscape/seascape level, ecological zones, and habitat types. The model's purpose is to develop target levels for ecological indicators that improve, increase, restore, and protect aquatic and terrestrial habitats and ecological functions in the San Francisco Bay-Delta River system. The target levels for the ecological indicators are assumed to support self-sustaining, diverse, balanced, and healthy populations of native species (Levy et al. 1996). For each level of organization, the user can specify a number of ecological indicators in order to characterize the overall health of the system. For rivers, the extent and quality of edge habitat is characterized by channel length, ratio of current and historical channel length, length of SRA bank, length of rip-rap bank, and areal extent of classes of riparian vegetation.

An ecosystem performance model has been developed as a chinook salmon management tool for the Columbia River basin (Mobrand et al. 1997). The model provides a conceptual framework that evaluates salmon performance in terms of life-history diversity, productivity, and capacity, giving more temporal and spatial detail than models that focus solely on productivity. Life history diversity is represented by the range of population segments composed of individuals that share the same locations at the same time while completing their life cycles. Performance potential is measured in terms of the rivers' ability to allow diverse salmon life history patterns to persist. Productivity is defined as the largest expected survival and is represented by the Beverton and Holt survival function. Capacity regulates potential abundance and is affected by the amount of habitat, available food, and predator abundance and behavior. Unlike productivity, capacity does not affect individual survival at low population densities. The performance model incorporates productivity and capacity with connectivity of habitats that salmon need to complete their life history trajectories.

Richter et al. (1997) describes hydrological variability as an indicator of ecosystem integrity. Flow targets needed to sustain native aquatic biodiversity and protect natural ecosystem river functions are identified. The model is for use in systems where the hydrological regime has been or could be significantly altered by human activities. Hydrological variability and its related characteristics of timing, frequency, duration, and rates of change are characterized by using the indicators of hydrologic alteration (IHA) method (Richter et al. 1996). The IHA method derives 32 ecologically-relevant hydrological parameters that characterize interannual variation in the stream flow record. The method guides the process of characterizing the natural range of flow variation and requires that management targets be based on available ecological information representing natural, historic, or less-disturbed conditions. Change in river flow that fall within the interannual range of variation, as demonstrated by IHA values, are assumed to maintain ecosystem integrity.

IDENTIFYING APPROPRIATE PHYSICAL-BIOLOGICAL RELATIONSHIPS

The relationships included in a model are dependent on its purpose. As stated by Grimm (1999): "The purpose of a model is to capture the essence of a problem and to explore different solutions of it." A purpose of the EFM is to understand how flood-damage-reduction actions can be implemented to maintain or enhance aquatic ecosystem values. Aquatic ecosystem values are primarily related to the abundance and distribution of socially- and politically-important fish species, including species important to commercial and sport fisheries and species listed under the federal and California Endangered Species Acts. Relationships included in the EFM, therefore, should provide a measurement of ecosystem attributes that affect the abundance and distribution of fish species.

Relationships in the EFM must include variables that describe system behavior at locations and within timeframes relevant to the proposed flood-damage-reduction actions and to the ecosystem elements affected. Relationships describing the effects of flood-damage-reduction actions may be developed at many scales, including individual organisms, species populations, habitats, communities, stream segments, and watersheds (Grimm 1999, Levy 1996, Frissel et al. 1986). Relationships identified in this report are selected based on two broad premises. First, habitat abundance and quality affect fish population abundance and distribution, food resources available, and the effects of predation and competition (Frissel et al. 1986). Second, ecosystem processes and structure, primarily geomorphic and hydrologic, determine the structure and dynamics of the river and floodplain and the subsequent creation and maintenance of fish habitat (Sparks 1995, Ligon et al. 1995, Frissel et al. 1986). Tables B-1 and B-2 illustrate ecosystem and habitat relationships for chinook salmon and splittail in the Sacramento–San Joaquin River system.

As described in the main text of this report, the aquatic ecosystem model has two primary geographic elements, the stream channel and the floodplain, including the flood bypasses. The stream channel element supports aquatic species throughout the year. In the Sacramento–San Joaquin River system, floodplain and flood bypasses provide essential seasonal habitats for aquatic

Table B-1. Ecosystem and Habitat Relationships for Life Stage Events of Chinook Salmon for the Stream Channel

Variable		Species Response	
cosystem Process or Structure	Habitat Condition	Individual	Population
Stage Event: Chinook Salmon Adult Migration			
v nnel morphology	depth velocity	adult passage	egg production
v ier structure nnel morphology	barrier height barrier length approach pool depth	adult passage	egg production
v rvoir release temperature nnel morphology	water temperature	adult survival	egg production
Stage Event: Chinook Salmon Adult Holding/Spawning			
v nnel morphology	pool depth, width, length cover	adult survival	egg production
v ment movement nnel morphology	flow depth and velocity gravel area, elevation, thickness, and quality	spawning	egg production
v rvoir release temperature nnel morphology	water temperature	adult survival	egg production
Stage Event: Chinook Salmon Egg Incubation			
v ment movement nnel morphology	velocity gravel elevation, quality	egg scour	fry abundance
v nnel morphology	depth gravel elevation	egg dessication	fry abundance
v nnel morphology	velocity hydraulic gradient sediment permeability	egg and larvae suffocation	fry abundance
v rvoir release temperature nnel morphology	water temperature	egg survival	fry abundance
Stage Event: Chinook Salmon Juvenile Rearing and Movement			

Variable		Species Response	
cosystem Process or Structure	Habitat Condition	Individual	Population
w ment movement nnel morphology rian vegetation	depth velocity cover	juvenile survival juvenile growth	smolt abundance
w rvoir release temperature nnel morphology	water temperature	juvenile survival juvenile growth	smolt abundance

Table B-2. Ecosystem and Habitat Relationships for Life Stage Events of Chinook Salmon and Splittail for Seasonally Inundated Floodplain and Flood Bypasses

Variable		**Species Response**	
Ecosystem Process or Structure	**Habitat Condition**	**Individual**	**Population**
Life Stage Event: Chinook Salmon Adult Migration			
flow barrier structure bypass morphology	barrier height barrier length approach pool depth	adult passage	egg production
Life Stage Event: Splittail Adult Spawning and Egg Incubation			
flow floodplain/bypass morphology floodplain vegetation	depth area spawning substrate	spawning egg survival	larval abundance
Life Stage Event: Chinook Salmon and Splittail Juvenile Rearing and Movement			
flow floodplain/bypass morphology floodplain vegetation channel morphology	depth area cover affected cross-sectional area of river channel	juvenile growth juvenile survival	juvenile abundance smolt abundance
flow floodplain/bypass morphology	perennial pond area	juvenile predation	juvenile abundance smolt abundance
flow floodplain/bypass morphology	depth pond isolation drainage area	juvenile movement juvenile survival	juvenile abundance smolt abundance

species that allow expression of life history types that are different than would occur in the stream channel alone. Greater life history diversity contributes to increased species population productivity, potentially increasing resilience and resistance of the population to annual fluctuations in abundance under variable environmental conditions (The Independent Scientific Group 1996, Watson 1992). In addition, fish species diversity and population abundance is generally higher with increased floodplain area and duration of floodplain inundation (Ligon et al. 1995).

Development of some of the elements of the aquatic ecosystem model not directly related to floodflow management has been deferred at the direction of the Corps. This appendix describes the results of our literature review for the remaining elements, followed by the rationale we used in determining the relationships recommended in the main text of this report.

I. STREAM CHANNEL

Although the relationships in the model are ecosystem level indicators, the relevance of the timing and location of ecosystem processes and structure that determine habitat conditions will vary by species and species life history events. The stream channel model element potentially has four major sub-elements, representing life history events in the life cycle of chinook salmon. Chinook salmon are selected as the representative species for the stream channel because they are sensitive to an important cross section of ecosystem attributes, they are native to the system and use a range of habitats important to other native species in the aquatic community, and they are targeted for restoration under the federal and California Endangered Species Acts, CALFED, and the Central Valley Project Improvement Act (CALFED 1998, National Marine Fisheries Service 1997, U.S. Fish and Wildlife Service 1997). The four major life history events for chinook salmon are adult migration, adult holding and spawning, egg incubation, and juvenile rearing and movement (Figure B-1, Figure B-3). Restoration and maintenance of chinook salmon populations requires successful completion of all life history events.

The discussions that follow for each fish life-history event describe microhabitat conditions, providing background information relative to habitat needs of individual fish. Microhabitats, however, are an inappropriate scale for assessment of flood-damage-reduction actions. Most management actions would affect environmental conditions through an entire river reach or segment, not just microhabitat at specific locations. Also, the available physical models simulate flow and morphology at a river reach or segment scale and do not capture the spatial or temporal scale of microhabitat or bedload (e.g., pools and riffles). Watershed or ecosystem indicators of habitat conditions are at a more appropriate scale. Ecosystem processes and structure determine habitat conditions because changes in a large-scale system change the capacity of all lower-level systems that it encompasses (Frissel et al. 1986). Maintenance of segment- and reach-integrity is assumed to maintain habitat and preserve the resilience of the associated biological community. The relationships identified include geomorphic and hydrologic elements that affect the physical variability of aquatic habitats.

E. Juvenile Rearing and Movement

E-1. Rearing Habitat Abundance

Rearing habitat, on a microhabitat scale, is defined by depth, velocity, and cover. Juvenile chinook salmon are most abundant where substrate particles are small, velocity is low, and depth is shallow (Everest and Chapman 1972 as cited by M.C. Healey 1991). Everest and Chapman (1972) reported newly-emerged chinook salmon inhabiting pools and eddies at depths greater than 15 cm (0.5 ft) and velocities < 50 cm/s. The density of juvenile chinook salmon was lower when velocity was ≥60 cm/s. Murphy et al. (1989) found that juvenile chinook were rare in still water or where velocity was greater than 30 cm/s.

Geographically specific microhabitat preferences for chinook salmon have been developed in the Sacramento River System. Velocity and depth suitability curves representing the habitat preferences of chinook salmon fry in the lower American River describe a range in velocity of 4.6 to 9.1 cm/s (0.15-0.30 ft/s) and a depth ranging from 21.3 to 30.5 cm (0.7–1.0 ft) (US Fish and Wildlife Service 1985, cited by Raleigh et al. 1986). As juvenile chinook salmon grow they move to faster and deeper water with larger size substrate that may provide more food sources and protection from predators (Raleigh et al. 1986). Juvenile chinook salmon larger than fry prefer flow velocities ranging from 12.2 to 24.4 cm/s (0.4–0.8 ft/s) and depths that range from 30.5 to 76.2 cm (1.0–2.5 ft)

Juvenile chinook salmon seek cover and velocity refuge in the form of gravel, cobble, rocks, boulders, and instream woody material. Peters et al. (1998) compared fish densities with a number of habitat variables at 67 sites in 15 rivers of western Washington. Overall, fish densities were positively related to the percent of the site with overhead riparian cover and instream wood cover. Relationships provided by Raleigh et al. (1986) assumed that approximately 20% cover is adequate for juvenile chinook salmon, but available studies do not clearly support the assumption. A community based habitat suitability index model for SRA cover for selected reaches of the Sacramento River system determined that the SRA cover, including the area covered by overhanging vegetation and in channel structure, achieves a maximum habitat value to fish and other species at 75 % (Fris and DeHaven 1993). Instream wood cover is important to juvenile chinook salmon because it provides protection from predators, increases food resources, and improves nearshore hydraulic and water quality conditions, thus contributing to higher growth rates (Raiser and Bjornn 1979 in Fris and DeHaven 1993).

As noted previously, ecosystem processes and structure determine habitat conditions because changes in a large-scale system change the capacity of all lower-level systems that it encompasses (Frissel et al. 1986). The flow velocity, depth, and cover components of suitable microhabitats discussed above are driven by ecosystem-level processes and structure, including hydrology, sediment movement, channel morphology, and extent of woody riparian vegetation. Thus, key assumptions and relationships at the ecosystem level that define suitable rearing habitat involve 1) flows needed to maintain suitability of spawning gravel substrates for early rearing, 2) flows promoting channel migration to maintain channel complexity, and 3) presence of woody bank vegetation to provide overhead cover and instream cover recruitment during channel migration. These assumptions and relationships are described below.

Formulation of Recommended Assumptions and Relationships

Recommendation 1. The movement and supply of gravel 2–15 cm in diameter to a river reach must be sufficient to maintain existing gravel substrates and bedload that provide rearing habitat for juvenile chinook salmon. Periodic scour is needed to maintain invertebrate communities and to remove fines that fill the spaces between gravel particles. To maintain juvenile rearing habitat quality and quantity provided by gravel substrates, peak flows must mobilize gravels up to at least 10 cm in diameter during nearly all years. These peak flows must occur in the rearing reaches where source proximity and stream gradient permits the presence of gravel substrates. An incipient motion analysis can be applied in suitable reaches to determine changes in frequency of flows mobilizing 10 cm diameter particles between without-project and with-project conditions.

Discussion. Pool/riffle morphology (i.e., bedload) is determined by the slope of the reach, input of sediments, and flow (Frissel et al. 1986). Riffle and pool form reflect the structure inherited from previous flood events, where riffles are zones of deposition and pools are zones of scour. Only large storm events can mobilize coarse gravels and cobbles affecting bedload. Natural high flows on unregulated streams provide the necessary amount of bed mobilization to carry out fine sediments and restore ecosystem integrity (Richter et al. 1996 and 1997). A regulated stream may lack the periodic high flows that would normally flush fine sediments from the gravel and maintain bedload (Raiser et al. 1985). Peak flows are needed to scour river beds, prevent the accretion of fine sediments, and maintain communities of aquatic invertebrates that provide food for fish (Power et al. 1997, Reice 1994, Milhous 1998).

Most benthic aquatic macroinvertebrates are more abundant in riffles than in pools (Rabeni and Minshall 1977; Huryn and Wallace 1987; Brown and Brussock 1991, cited in Hilderbrand et al. 1997). The range of velocities that occur in riffles is considered important to food availability and feeding efficiency for juvenile chinook salmon. Hydraulic parameters, such as dispersive fraction and velocity, can be useful to predict the proportion of food organisms returning to the substrate after disturbance. Lancaster et al. 1996 compared four streams with contrasting hydraulic transport characteristics. The stream channel with the highest mean velocity had the lowest proportion of food organisms returning to the substrate per meter traveled (i.e., the greatest exposure to fish predation). However, velocity, channel specific depth, and turbulence may account for different return rates in streams with similar area of zero velocity zones.

Peak flows are also needed to insure channel movement, create new midchannel bars and islands, and recruit gravel and cobbles from the floodplain (Ligon et al. 1995). Peak flows, however, result in the net downstream movement of gravel and cobble. Channel morphology and sediment flow, therefore, must be maintained to allow peak flows to recruit sediments through transport from upstream sources and bank erosion. Hazel (1976, cited in Burt and Mundie 1986) suggests that peak flows should not be reduced by more than 30 % of their natural regime since reducing peak winter and spring flows would reduce the ability of the river to maintain or renew its physical structure. Annual peak flows flush sediments and debris from the system, initiate bank erosion, and develop pools.

Gravels and cobbles provide cover for juvenile chinook salmon and habitat for aquatic insects important as food. The size of the gravel important as spawning habitat for chinook salmon is assumed to provide adequate water flow and oxygen for invertebrate production and juvenile rearing. Suitable spawning gravel ranges in size from approximately 0.3 to 15 cm (Raleigh et al. 1986). The upper range of spawning gravel size depends upon the size of spawner, but the optimal size range was estimated to be about 2 to 10.6 cm.

Recommendation 2. Channel migration promotes channel-habitat complexity, particularly by promoting recruitment of instream woody material. The without-project and with-project flow regimes can be compared to determine if channel migration, and therefore channel complexity, will increase or decrease with application of an action. The average rate of channel migration is approximately related to floodflows with return periods between 1.5 and 5 years. If an action results in an increase in the 1.5-year and the 5-year flow, the rate of channel migration will increase. If these flows decrease, the rate of channel migration will decrease. Increased channel migration throughout most of the Sacramento–San Joaquin River system is considered ecologically beneficial, while decreased channel migration is considered ecologically detrimental.

Discussion. The relationship of channel migraton to flow regime is discussed in detail in Appendix A under sub-element B-1.

Channel migration is important in maintaining diversity of bedform and recruiting woody material to the stream channel through erosion of banks and capture of adjacent riparian vegetation. Flow regulation may interfere with the downstream natural disturbance regime, including channel migration (Ward and Stanford 1995).

The dynamics of large woody debris (LWD) on the Sacramento River system has been altered by the reduction of natural LWD recruitment and retention. Riprapping not only removes trees but it also stops erosion, reducing the ability of the bank to capture and retain new wood. The smooth and hardened surface along the riprapped shoreline prevents LWD from become securely snagged and anchored in the sediment. As a result, limited erosion reduces channel complexity by reducing new accreted habitats, changing sediment and organic storage and transport, and reducing lower food web production (DeHaven 1999).

Among the factors affecting LWD's spatial stability are length, orientation, degree of burial and whether LWD is found as a single log or as aggregates. Hilderbrand et al. (1998) determined that logs shorter than the average channel width (5.5 m) moved significantly more frequently than the logs 1.5 to 2 times the average channel width. These results support other studies findings (Hilderbrand et al. 1998 citing Linkaemper and Swanson 1987, Bilby 1984, Robinson and Beschta 1990). Log orientation and degree of burial influences debris movement. LWD positioned less than 30 degrees relative to the axis of the flow is much more stable than debris with and angle of orientation greater than 60 degrees (Bryant 1983, cited by De Haven, 1999). Also, debris anchored to the stream is more stable than LWD with only one or neither end secured (Bilby 1984 in DeHaven 1999). Aggregates of LWD may be more effective than individual logs in creating and maintaining pools (Carson et al. 1990 in Hilderbrand et al. 1998). LWD oriented as ramps and dams perpendicular to stream flow typically increases channel scouring (Hilderbrand et al. 1998).

LWD not only provides habitat for fish and aquatic invertebrates but it also influences channel morphology by promoting storage of sediments and particulate organic matter which in turn increases the area and depth of pools that juvenile salmonids prefer (Bisson et al. 1988 cited by Beechie and Sibley, 1997; Hilderbrand et al. 1998). Most benthic aquatic macroinvertebrates are more abundant in riffles than in pools (Rabeni and Minshall 1977; Huryn and Wallace 1987; Brown and Brussock 1991, cited in Hilderbrand et al. 1997). Instream woody material could, by changing the proportional area of pools and riffles in streams, affect the abundance of benthic macroinvertebrates and therefore food available to fish and other benthic predators (Hilderbrand et al. 1997).

Instream woody material and vegetation provide food and habitat for invertebrates which in turn are food for fish (Hydrozoology 1976 and Sekulich and Bjornn 1977 in USFWS 1992). In some rivers, fish feed on benthic organisms associated with instream woody material, especially when other organic material is relatively unavailable for invertebrate colonization (Angermeir and Karr 1984). Material entering the stream from terrestrial vegetation would be expected to increase food production. In the littoral zone of lakes, increased woody material increases nutrient cycling and productivity (Christensen et al. 1996, citing Wege and Anderson 1979). Particulate organic matter is a primary food for invertebrates and is higher in association with instream woody material than with other substrates (Bilby and Ward 1991, citing Naiman and Sedell 1979; Bilby and Likens 1980).

Both small and large instream woody material can provide cover for small fish and protection from predators (Spalding et al. 1995). Vulnerability to bird and mammal predation is likely greatest during periods of low flow (Angermeir and Karr 1984), probably a result of restricting habitat to shallow depths. The value of instream woody material in providing fish with protection from bird and mammal predators should be greatest during low flow periods and in shallow depths. However, juvenile fish are vulnerable to predation by other fish species in deeper habitats (Schlosser 1991), and cover, including cover provided by instream woody material, is an important habitat attribute.

Recommendation 3. To provide overhead cover and instream-cover recruitment during channel migration, river banks and floodplains should support woody riparian plants. The presence of woody bank vegetation is dependent upon the proximity of the woody riparian zone to the channel during the low-flow periods. Project-induced changes in this proximity can be measured by projected changes in the location of the lower boundary of the potential riparian zone, as described in Sub-element A-5 of Section 2 (terrestrial EFM) relative to projected changes in the location of the average-August edge of water. Increased proximity is ecologically beneficial.

Discussion. Riparian vegetation plays a major role in the linkage between terrestrial and aquatic habitats by serving as a source of large woody debris and a reservoir that takes up nutrients during periods of rapid plant growth and releases them gradually into the stream through litter fall and decomposition (Whiting 1998). Raleigh et al. (1986) suggests that in low- to moderate-gradient landscapes, a 30 m vegetated buffer strip along each side of the stream will protect banks from erosion, potentially moderating sediment input to the stream and providing cover and food sources. As discussed above, large woody debris recruited to the river channel provides habitat for fish and aquatic invertebrates (Bisson et al. 1988 cited by Beechie and Sibley, 1997; Hilderbrand et al. 1998). Small shallow sloughs lined with emergent vegetation also provide protection from piscivorous fish as well as providing sources of food (Daniels and Moyle 1983).

Riparian vegetation is an important food source for shredders in streams (Wipfli 1997 citing Cummins et al. 1989) as well as detritivores that feed on leaf litter. Leaf litter and wood that enter the aquatic system are consumed and processed by microbial and benthic communities constituting a major source of nutrients and food for fish species (Wipfli, 1997 citing many studies). This additional input to the food base for aquatic invertebrates translates into higher growth rates and ultimately an increase of aquatic prey for fish (Wipfli 1997). Riparian vegetation also provides terrestrial-derived invertebrates that contribute to the fish diet, specially in environments of reduced water and substrate quality (Wipfli 1997).

II. FLOODPLAINS AND FLOOD BYPASSES

The floodplain and flood-bypass model element has three sub-elements representing life history events in the life cycle of chinook salmon and splittail. In addition to the stream-channel habitat discussed above for chinook salmon, floodplain and flood bypasses provide important rearing habitat for juvenile chinook salmon. Splittail are included along with chinook salmon in development of relationships because their habitat needs encompass additional attributes relative to timing, magnitude, and duration of flood events. Like chinook salmon, splittail are native to the system and they are targeted for restoration under the federal Endangered Species Acts and by CALFED (U.S. Fish and Wildlife Service 1996). The major life history events include adult migration for chinook salmon, adult spawning and egg incubation for splittail, and juvenile rearing and movement for chinook salmon and splittail (Figures B-1 and B-2; Figures B-3 and B-4).

The prime physical processes affecting fish habitat of floodplain ecosystems are inundation and sediment erosion and deposition (Sparks 1995). Key habitat relationships discussed below are primarily focused on floodplain inundation potentially important to both chinook salmon and splittail.

B. Adult Spawning and Egg Incubation

B-1. Spawning Habitat Abundance

The availability of spawning habitat for splittail is related to flood timing, magnitude, duration, and frequency relative to floodplain and flood bypass morphology. The timing of splittail spawning and egg incubation is shown in Figure B-4.

Formulation of Recommended Assumptions and Relationships

Recommendation 1. Increasing the inundated area of vegetated floodplain and flood bypasses, by increasing the magnitude or frequency of overbank flows or the floodplain area, increases fish population abundance.

Discussion. The strongest year classes of splittail have occurred in extremely wet years (e.g., 1982, 1983, 1986, and 1995) when floodplain- and flood-bypass inundation is extensive and fairly continuous during the spawning season. The relationship between fish abundance and bypass flooding (i.e., days of inundation) indicates that the strongest year classes are associated with periods of floodplain inundation lasting at least one month (Sommer et al. 1997). Longer periods of inundation, however, are also correlated with greater floodplain area. Increasing the inundated area during lower flow years, given that the inundation period is sufficient, may benefit splittail through increased availability of spawning habitat.

Recommendation 2. Terrestrial vegetation in the floodplain and flood bypasses should be inundated for at least 21 to 28 consecutive days between February and May to provide habitat for splittail spawning. (Flooding prior to February may be important to attract adults upstream and to provide forage habitat for adult splittail, but adult splittail migration is currently not well understood.) A minimum multi-year recurrence frequency for flows needed to inundate the floodplain is required to sustain splittail populations; a 2-3 year return period will support adequately-frequent spawning, while a 4-year return period may not (i.e. a maximum suitable return period of 3 years may be assumed). The without-project and with-project flow regimes can be examined to determine the maximum stage of overbank flows meeting these timing, duration, and frequency criteria for each condition, and changes in extent of inundation meeting these criteria can be therefore be depicted.

Discussion. To maximize potential use by splittail of floodplain habitat, adults should be provided unimpeded access to vegetated floodplain and flood bypasses during the primary spawning season (February through May). Spawning has generally been reported to begin in late February or early March, with peaks in late March and April (Baxter et al. 1996). Initial laboratory studies indicate that at least 10-14 days are required for fertilized splittail eggs to develop into free-swimming fry, depending on water temperature (Bailey pers. comm., as cited by Sommer et al. 1997). Because of uncertainty regarding the amount of time adults need to find potential habitat and begin spawning, a minimum period of 3 to 4 weeks of continuous inundation is recommended during February-May. The duration of inundation must be sufficient to permit adult immigration and spawning, egg incubation, and larval development of a swim bladder. Completion of these events would result in free-swimming fry capable of moving passively or actively from spawning areas to perennial waters as flood waters recede. Inundation prior to the spawning period may increase habitat value by providing additional forage habitat for adults. An adequate recurrence frequency for the occurrence of such flows required to sustain the populations is 2-3 years; a frequency greater than 4 years may not sustain them.

Recommendation 3. The area of suitably frequent inundation should be overlain with the depiction of potential riparian zones (Zones 2-5) and mapping of upland and agricultural vegetation, for without-project and with-project conditions, to determine changes in the areas of inundation for each vegetation type.

Discussion. The vegetated portion of the area inundated according to the criteria identified in Recommendation 2 needs to be determined to assess the change in suitable habitat. It is assumed that vegetated areas have higher value than unvegetated areas. However, value probably varies by vegetation type, and the value of a particular vegetation type may depend on the specific nature of the inundation event, such as depth of inundation, flow velocity, duration, and other factors. The interplay of these potential factors is not presently known, so we cannot recommend a more detailed model element. At a minimum, however, types of agricultural uses should be identified in affected areas to whether vegetation will, in fact, be present during the periods of inundation. Furthermore, we recommend that the comparison of without- and with-project estimates of vegetated area meeting the inundation criteria be summarized by type of vegetation (e.g. according to the recommended individual zones of potential riparian and wetland vegetation as described in Section 2 and Appendix A, as well as by agricultural crop type and upland vegetation community type). This will allow at present a subjective assessment of the relative importance of the without- to with-project change in inundated area, and will in the future allow, as results from research becomes available, the development of a more detailed assessment of changes in habitat value.

C. Juvenile Rearing and Movement

Seasonally inundated floodplains and flood bypasses provide important rearing habitat for both juvenile chinook salmon and splittail. Sand-bed rivers, as represented by the lower segments of the Sacramento River and its tributaries, do not produce large numbers of invertebrate prey for fish, therefore inundated floodplains are important as foraging grounds (Ligon et al. 1995). In addition, floodplains are important to juvenile fish as refuge from predators (Welcomme 1989 in Ligon et al. 1995). Off-channel ponds, similar in function to inundated floodplain, have been shown to provide habitat for juvenile chinook salmon. Richards et al. (1992) indicated that off-channel ponds connected to the river may increase rearing habitat for juvenile chinook salmon in the Yankee Fork of the Salmon River by providing low water velocity (<30 cm/s) and moderate depths (0.1-0.5 m). Fish densities in connecting channels and ponds with instream cover had fish densities similar to those described in natural channel habitats. Swales and Leving (1989) suggest that summer migration of juvenile coho to off-channel ponds may be an avoidance response to the high variable main-channel flows. These off-channel ponds, compared to the main river, provide more stable environmental conditions as well as greater food production which in turn allow for higher growth rates.

Rearing of juvenile splittail and chinook salmon coincides with winter flood events that inundate floodplains and flood bypasses (Figures B-3 and B-4) (California Department of Water Resources 1999, Jones & Stokes 1999). High flows also appear to increase the density of juvenile chinook salmon in downstream habitats (Kjelson et al. 1981 in Stevens and Miller 1983, U.S. Fish and Wildlife Service 1994), including the large expanses of floodplain and floodbypass in the lower segments of large rivers. Key factors affecting rearing success include habitat abundance, predation, and connectivity with the river channel.

Water temperature is not considered in relationships for floodplain and flood bypass rearing by chinook salmon and splittail. Although water temperature is important to successful rearing conditions, the range of temperatures available during flood events is assumed to meet species needs relative to survival and growth. Water temperatures in floodplain habitats are highly variable because of variable depth, connectivity to the river channel, shade, season, and broad expanses of open water. Exposure of juvenile splittail and chinook salmon to specific water temperature is further complicated by movement of individuals.

C-1. Rearing Habitat Abundance

The area of habitat for rearing by juvenile chinook salmon and splittail is related to flood timing, magnitude, frequency, and duration relative to floodplain and flood bypass morphology. In addition, floodplain and flood bypass habitat offer protection from large piscivorous fish such as striped bass (Welcomme 1989 in Ligon et al. 1995). It is important that rearing habitat exclude large predatory fish and minimize predation opportunities on juvenile splittail and chinook salmon. Key features of rearing habitat that serve to exclude predatory fish include relatively shallow depths, dense cover provided by flooded vegetation, and the temporary availability of floodplain habitat which prevents development of high predatory fish densities.

Formulation of Recommended Assumptions and Relationships

Recommendation 1. Increasing the inundated area of vegetated floodplain and flood bypasses, by increasing the magnitude or frequency of overbank flows or floodplain area, increases fish population abundance.

Discussion. As noted above, the strongest year classes of splittail have occurred in extremely wet years when floodplain and flood bypass inundation is extensive and fairly continuous during the splittail spawning season (Sommer et al. 1997). As shown by Stevens and Miller (1983), chinook salmon abundance increased about 12% for every 100 m^3/ second of daily mean December flow and 7% for each 100 m^3/ second of daily mean October-February flow. This study as well as others suggest that high flows improve production of juvenile chinook salmon by potentially increasing survival, growth, and movement through reduced predation and increased channel velocity, food availability, and habitat area. In general, high river flows during or after spawning season improves the quantity and quality of habitat available for all juvenile fish, not only for chinook salmon (Stevens and Miller 1983).

Floodplain vegetation plays a major role in the linkage between terrestrial and aquatic habitats by serving as a reservoir that takes up nutrients during periods of plant growth and releases them during periods of inundation through transport and decomposition (California Department of Water Resources 1999). Terrestrial vegetation is an important food source for shredders in streams (Wipfli 1997 citing Cummins et al. 1989) as well as detritivores that feed on leaf litter and other plant material. Leaf litter and wood that enter the aquatic system are consumed and processed by microbial and benthic communities constituting a major source of nutrients and food for fish species (Wipfli, 1997 citing many studies). This additional input to the food base for aquatic invertebrates translates into higher growth rates and ultimately an increase of aquatic prey for fish (Wipfli 1997). Increasing the inundated area during lower flow years, given that the inundation period is sufficient, may benefit juvenile splittail and chinook salmon.

Recommendation 2. Terrestrial vegetation in the floodplain and flood bypasses should be inundated from December to May to provide rearing habitat for juvenile chinook salmon and splittail. Inundation durations of greater than 8 weeks are optimal. For splittail, these conditions must occur in the same year when the spawning conditions are met (see Section B-1 above). Thus, a maximum suitable return period of 3 years may be assumed. The without-project and with-project flow regimes can be examined to determine the maximum stage of overbank flows meeting these timing, duration, and frequency criteria for each condition, and changes in extent of inundation meeting these criteria can be therefore be depicted.

Discussion. To maximize potential use by splittail and chinook salmon of floodplain habitat, juveniles should be provided unimpeded access to vegetated floodplain and flood bypasses during the primary rearing season from December through May (Figures B-3 and B-4). The benefit of floodplain habitat to juvenile rearing is dependent on duration of inundation. In general, juvenile splittail prefer shallow-water and well-vegetated habitat (Meng and Moyle, 1995). Splittail larvae and juveniles remain in shallow, weedy areas until water recedes, and then move into deeper water. As indicated by salvage patterns at the CVP and SWP fish facilities, juvenile splittail remain in habitat upstream of the Delta until May or June. Access to floodplain habitat may be beneficial to splittail growth and survival throughout the period when rearing occurs upstream of the Delta.

A study conducted by the California Department of Water Resources (1999) found that growth rates for juvenile chinook salmon released in the Yolo Bypass were higher than those for juveniles released in the Sacramento River channel, resulting in average smolt lengths of 93.7 mm and 85.6 mm respectively. Jones and Stokes (1999) findings support the assumed benefits of floodplain habitat in providing high growth rates. The study indicated that fall-run sized chinook salmon may have increased in length up to 1 mm each day. Juvenile salmon using floodplain habitat also appeared not to exit the floodplain until they reached smolt size or until drainage and other factors (e.g., water temperature) forced them to leave.

Juvenile chinook salmon may move into floodplain habitat at a length of less than 50 mm (California Department of Water Resources 1999, Jones & Stokes 1999). Assuming a maximum growth rate of about 7 mm in length per week, growth to a smolt size of about 80 mm would require 30 days or slightly more than 4 weeks. Juvenile chinook salmon could benefit substantially from inundation periods extending over the December through April period that last at least 8 weeks. Depending on initial fish size, food availability, and water temperature, juvenile chinook salmon would also benefit from shorter periods of inundation. Inundation periods longer than a few days increase habitat value by extending the availability of floodplain habitat for juvenile chinook salmon, allowing more juveniles to move into floodplain habitat and maintaining the habitat juveniles grow to smolt size.

Recommendation 3. The area of suitably frequent inundation should be overlain with the depiction of potential riparian zones (Zones 2-5) and mapping of upland and agricultural vegetation, for without-project and with-project conditions, to determine changes in the areas of inundation for each vegetation type.

Discussion. The vegetated portion of the area inundated according to the criteria identified in Recommendation 2 needs to be determined to assess the change in suitable habitat. It is assumed that vegetated areas have higher value than unvegetated areas. However, value probably varies by vegetation type, and the value of a particular vegetation type may depend upon the specific nature of the inundation event, such as depth of inundation, flow velocity, duration, and other factors. The interplay of these many potential factors is not presently known, so we cannot recommend a more detailed model element. At a minimum, however, types of agricultural uses should be identified in affected areas to whether vegetation will, in fact, be present during the periods of inundation. Furthermore, we recommend that the comparison of without- and with-project estimates of vegetated area meeting the inundation criteria be summarized by type of vegetation (e.g. according to the recommended individual zones of potential riparian and wetland vegetation as described in Section 2 and Appendix A, as well as by agricultural crop type and upland vegetation community type). This will allow at present a subjective assessment of the relative importance of the without- to with-project change in inundated area, and will in the future allow, as results from research becomes available, the development of a more detailed assessment of changes in habitat value.

C-3. Habitat Connectivity

Juvenile chinook salmon and splittail must return to the main river channel after rearing in floodplain and flood bypass habitat or they will die. Based on observations by fish biologists, juvenile chinook salmon and splittail remaining in isolated floodplain ponds do not survive through the summer (Jones & Stokes Associates 1999). In regulated streams, side channels may be a source of mortality for juvenile fish when these habitats become isolated pockets of water (Bradford 1997).

The movement of juveniles out of floodplain habitat is dependent on the timing and duration of inundation. As with movement within the stream channel, movement from floodplain and flood bypass habitat occurs as an expression of the interaction of genetic disposition and the environment, including habitat, food availability, water temperature, and flow conditions during rearing. Bradford (1997) indicated that fewer fish became stranded when water temperature is 12°C than when the temperature is 6°C and water levels decrease slowly. Water temperatures in the floodplain and floodbypasses of the Sacramento River, however, is generally near or above 12°C and the effect of water temperature on fish movement is not currently documented. Smoltification, the physiological process that occurs prior to juvenile salmon entering salt water, is the primary determinant for timing of juvenile chinook salmon migration to the ocean (Hoar 1976, Schreck 1981). In addition, falling river stage drains floodplain and flood bypass habitat, forcing movement to the stream channel (California Department of Water Resources 1999, Jones & Stokes Associates 1999).

Connectivity is the opportunity for fish to return to the main river channel during the period of falling stage after a flood event. Connectivity is a key factor affecting survival when stage falls and the floodplain begins to drain. Connectivity is dependent on floodplain and flood bypass topography.

Formulation of Recommended Assumptions and Relationships

Recommendation 1. The area of isolated ponds with a depth exceeding 1 foot when flow corresponds to the mean April flow or mean the May flow, whichever is highest, as well as the area that drains through such ponds, is an indicator of connectivity. Increases in one or both of these acreages in considered ecologically detrimental, while reductions are considered ecologically beneficial. Without-project and with-project floodplain topography can be compared based on this indicator. Actions that include floodplain grading intended to reduce detrimental conditions can readily be incorporated into this analysis.

Discussion. The minimum depth of 1 foot is based on preliminary understanding of fish movement and field observations of stranding in floodplains and flood bypasses of the Sacramento River system (Jones & Stokes Associates 1999, California Department of Water Resources 1999). Withhout- and with-project digital terrain models (DTMs) may be used to estimate acreages of ponds meeting the isolated-pond criteria (i.e., areas of closed depression exceeding the depth threshold) and the drainage area of the ponds. Increases in pond or drainage area acreages is considered ecologically beneficial.

Recommendation 2. Connectivity is assumed to have minimal effect on survival when inundation of the flood plain and flood bypasses lasts through April for chinook salmon and May for splittail. The without-project and with-project flow regimes can be examined to determine changes in the frequency of such long-duration events.

Discussion. The floodplain in the Sacramento River provides rearing habitat for juvenile fish that is important to maintain until downstream migration begins. Juvenile chinook salmon and splittail inhabit flooded areas where they find abundant food and protection from predators. Juvenile salmon migrate to the ocean during the process of becoming smolt. Smolt migration to the ocean extends at least from February to June, depending on the run (Sasaki 1966 in Stevens and Miller 1983). Given growth rates observed, most juvenile chinook salmon in floodplain habitats would be expected to reach smolt size before the end of April.

Downstream migration for juvenile splittail may depend upon their upper temperature tolerance of 27-28 °C (Baxter et al. 1995). Some reaches in the Sacramento River do not exceed the upper temperature tolerance and juvenile splittail may remain in the river through their first summer and fall, migrating in the spring after one year in riverine habitats. Floodplain habitat can warm substantially during April and May and, given the migration pattern represented by salvage at the CVP and SWP fish facilities, juvenile splittail are assumed to leave floodplain habitat by the end of May.

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APPENDIX C. HYDROLOGIC AND HYDRAULIC DATA AND ANALYSES FOR THE ECOSYSTEM FUNCTIONS MODEL

INTRODUCTION AND PURPOSES OF THIS APPENDIX

The functional relationships identified in the terrestrial and aquatic elements of the ecosystem functions model (EFM) are highly dependent on the hydrologic and hydraulic characteristics of the river channels and floodplains in the study area. Hydrologic and hydraulic information and analyses are necessary to develop input variables and metrics for these relationships. The required information and analyses are focused on hydrologic and hydraulic characteristics that drive or are indicators of ecological processes, which in many cases differ from those typically analyzed for flood damage reduction studies. The purposes of this appendix are to:

- define the hydrologic and hydraulic analysis required to support the EFM relationships;
- describe potential application of the hydrologic and hydraulic information in the relationships;
- review available information from the hydrologic and hydraulic studies currently in progress for the Corps' Comprehensive Study, and its application to the EFM; and
- summarize hydrologic and hydraulic information needs for the EFM, including those that are outside the scope of the studies in progress.

This appendix is organized to meet these purposes by first describing the general hydrologic and hydraulic information needs for the EFM, followed by a section describing the hydrologic and hydraulic information required in specific EFM relationships by sub-element. The potential application of the hydrologic and hydraulic information in the relationships, using digital terrain models (DTMs) and a Geographic Information System (GIS) are also described in this section. In the final sections, the available information from hydrologic and hydraulic studies currently in progress for the Comprehensive Study, and its applicability in the EFM relationships, is described, followed by a summary of hydrology and hydraulic information needed to developing an operational DTM.

HYDROLOGIC AND HYDRAULIC INFORMATION IMPORTANT TO ECOSYSTEM FUNCTIONS

The functional relationships described for the terrestrial and aquatic elements of the EFM are dependent on physical processes and characteristics of the river channels and floodplains in the study area. Hydrologic and hydraulic characteristics are used in many of the relationships to set elevations, define boundaries, or determine suitable geographic areas for ecological processes. The inter-dependency of physical processes and ecological functions is extremely complex. Recognizing this complexity, the functional relationships identify hydrologic and hydraulic characteristics that are significant drivers or indicators of ecological functions on a landscape scale.

This work effort focuses on the development of the relationships, and not on their implementation in a model. However, the practicality of collecting and analyzing hydrologic and hydraulic data for use in the relationships has been constantly considered in their development. In addition, the use of analysis results and computed metrics in the relationships have been considered in terms of spatial analysis in the EFM. For this purpose, a preliminary concept for using DTMs and GIS has been formulated to illustrate the methods by which EFM outputs would be obtained. These considerations are intended to ensure that the relationships developed in this work effort put the actual implementation of the EFM within reach, although the data collection and analysis required is still expected to be significant.

The required hydrologic and hydraulic information for EFM relationships is focused on frequencies, durations, timing, and hydraulic characteristics that are ecologically significant. This information, in many cases, is different from information typically required for flood damage reduction studies, although the required methods of analysis may be similar. The required information for the EFM reflects an emphasis on:

- lower flows, including summer flows and relatively frequent floods that play a significant role in channel forming processes.
- flow durations and flood frequencies that are significant biologically, such as the duration required for spawning success or spawning frequency for long term population viability.
- seasonal characteristics and timing, such as frequencies or flow durations during the growing season or during a spawning period.
- change and rates of change, such as the flows required to renovate gravel substrates or induce lateral migration, or the maximum recession rate of a hydrograph required to sustain seedlings.
- sequences of events that are significant biologically, such as a second peak in river stage that prevents germination of seeds deposited by the first peak.

In several of the relationships, ecological functions are tied to a sequence or combination of hydrologic and hydraulic characteristics, with the ecological outcome (and model output) determined by the intersection of various criteria.

A conceptual scheme for development of the required hydrologic and hydraulic information for the EFM has been developed that applies to many of the functional relationships, based on the emphasis noted above. This scheme includes the analyses required to characterize without- and with-project conditions in implementation of the EFM. These analyses may be used to screen or evaluate actions contemplated under the Comprehensive Study. The emphasis on lower flows, durations, and relationship-specific seasonal timing generally requires analysis of observed or synthesized daily flow data sets to develop the required metrics for the functional relationships. In general, the analyses will result in metrics at each of the cross section locations for the hydraulic models presently being developed for the Comprehensive Study. These metrics will be linked in the DTMs and GIS to provide EFM outputs. The conceptual scheme for EFM analysis includes the following components:

- Development of existing (without-project) mean daily flow data sets, by reach, that represent present conditions.
- Development of with-project mean daily flow data sets, by reach.
- Computation of specified hydrologic and hydraulic metrics for the relationships, using automated methods.
- Use of the computed metrics in a DTM to define elevations, depths, boundaries, or surfaces, or other topographic parameters.
- Compilation and management of DTM and other results in a GIS to map zones of suitability or quality for EFM outputs.

Mean Daily Flows

Mean daily flows are available for stream gages at many locations on the Sacramento and San Joaquin River systems. These data are expected to form the foundation for analysis of EFM relationships. Watershed changes and stationarity in the data sets should be analyzed to determine the period of record that is most representative of present conditions.

Although a large number of streamflow gages are available, an observed data set will not be available for many reaches in the system. These reaches will require synthesis of mean daily flows for analysis and use in the relationships. The with-project condition will also require synthesis of a representative data set for most relationships, if the action to be evaluated is expected to change the metric required in the EFM relationships. Existing operational hydrologic models (e.g., CAL-SIM) may be useful in synthesizing flows, but would require conversion to a daily, rather than monthly time step.

The data analysis required to support the EFM is expected to be significant, but well-within the capabilities of the study and modern computing methods. In some cases, synthesis and analysis of complete project life mean daily flow data sets may not be required. Considerable effort may be saved if the analysis process is driven by the anticipated effects of particular actions by reach, and not uniformly applied to the entire study area.

Stage-Discharge Relationships

The development of metrics for the EFM relationships will require conversion of flow data sets to river stages under various conditions. This computation is typically made using a hydraulic model. The hydraulic models presently being developed for the Comprehensive Study are intended to accurately represent flood conditions. These models are calibrated to flood flows, and their accuracy for use at flows lower than the 2-year return period may be limited. Hydraulic controls in the channel that are not identified in the existing model cross sections (e.g., riffles between cross sections) may control hydraulic conditions at low flows, but not be a significant influence at flood flows. In addition, effective roughness of the channel may increase with decreasing depth.

The appropriate method for computation of river stage from flow data will likely be reach- and relationship-specific, depending on the accuracy required. Potential options include using the hydraulic models presently being developed, recognizing limitations in accuracy; refining the hydraulic models to more accurately reflect low flow hydraulics; and developing stage-discharge rating curves at the cross sections from modeling results or measured water surfaces. Additional description of EFM applications of the hydrologic and hydraulic analyses presently being completed for the Comprehensive Study is provided in a subsequent section of this appendix.

Use of DTMs and GIS

A detailed prescription for the use of DTMs and GIS in the EFM is outside the scope of this work effort. However, it is clear that EFM outputs, like floodplain and flood damage reduction analysis results, must be presented and analyzed in spatial form. A discussion of the potential uses of DTMs and GIS is therefore included here to illustrate the application of EFM relationships using the computed hydrologic and hydraulic metrics. The development of particular topographic and spatial analysis techniques and methods could best be developed in a pilot study.

Computed metrics from hydrologic and hydraulic data may include elevations, depths, velocities, and other physical parameters. These metrics will generally be computed at each cross section, and converted to a boundary, zone, surface, or other feature using existing DTMs. A description of the available channel and floodplain geometry data is provided in a subsequent section of this appendix.

As an example of the use of DTMs, the stage corresponding to the maximum expected elevation for riparian germination success may be computed from a mean daily flow data set and a hydraulic model. The appropriate stage will be computed at each cross section, and these elevations linked in the DTM to form an elevation boundary on the ground surface below which successful germination is considered possible. A second relationship may produce a similar boundary at lower elevation below which germination is considered unsuccessful due to frequent inundation during the growing season. The DTMs will be used in a GIS to map, compare, compile, and manage the results from various relationships. Outputs for the EFM will generally be areas of ecological suitability or quality that can be displayed and quantified in the GIS. In the example above, the GIS will be used to map a suitability zone that lies between the two boundaries.

HYDROLOGIC AND HYDRAULIC INFORMATION REQUIRED FOR SPECIFIC RELATIONSHIPS

The description of the general computation scheme for EFM analysis provided above applies to several functional relationships. The specific requirements for individual relationships are described below. Unless otherwise stated, the general scheme applies. The reader is referred to the main text of this report (Sections 1 and 2) for a detailed description of each functional relationship. The relationships are referred to by name and number in this appendix, without repeating the text description. Hydrologic and hydraulic information required for each relationship is described below, with a brief description of specific analysis methods. A description of potential application of computed metrics in DTM/GIS analysis is also provided.

Terrestrial Element

Sub-Element A-2. Depth of Water Table

Required Hydrologic and Hydraulic Information

Elevation of shallow groundwater during late summer and early fall.

Shallow, near-stream groundwater levels are expected to vary seasonally, with the minimum stage during the growing season controlling suitability for the various vegetation zones. Where existing or projected shallow groundwater stage data are available in the potential riparian and wetland zones, these data may be used directly in the relationships described.

In the absence of such data, shallow groundwater levels may be estimated for use in EFM relationships using the average river stage in August. Groundwater levels in the riparian zone may be assumed to be level with this river stage. The accuracy of this estimate will vary depending on the geomorphic characteristics of the area, characteristics of the adjacent and underlying alluvium, groundwater hydrology in the area, and distance from the low flow channel.

In cases where shallow groundwater levels can be acceptably estimated from average river stage in August, an average August stage is developed by analyzing mean daily flow data sets to determine average August discharge in each reach. The associated stage is developed for without-project and with-project conditions at each cross section using a hydraulic model or stage-discharge rating curve. The groundwater surface is assumed level in the absence of actual data, or adjusted based on data obtained away from the main channel.

For without-project conditions, options to the methodology above may include using aerial photography and the DTM's, or observed stages, to develop the average August water surface. Projections of changes in water surface for the without-project condition may be possible using the hydraulic model or rating curves and estimates changes in average August discharge. This method would rely on the assumption that the observed water surface profile is representative of typical conditions.

Potential Application in DTMs and GIS. The estimates for shallow groundwater levels, derived as described above, are used in a DTM to define a groundwater surface. The depth to groundwater is generated using the DTM and mapped in a GIS according to the depth zones identified in the relationships. The depth zones represent areas of suitability for particular vegetation types. Potential vegetation zones for without- and with-project conditions are mapped based on estimated groundwater surface elevations for both conditions.

Sub-Element A-3. Flood Events Suitable for Plant Germination and Establishment

Required Hydrologic and Hydraulic Information.

Peak annual stages that satisfies seasonal timing and rate of recession criteria.

Flow frequency relationship derived from the above peak annual stages.

Stage-discharge rating curves at each cross section for discharges in the range of 1.5-year to 10-year return period.

Peak stages during the seed dispersal and germination periods for riparian species determine the availability of seeds to ground surfaces of varying elevations. The frequency at which inundation occurs determines the viability of the ground surface to support riparian vegetation types that rely on flood-borne seed dispersal versus later-successional species that do not. The peak stage required for germination and plant establishment must:

a. occur in the period between mid-April and mid-August; and
b. have a rate of recession less than or equal to 0.88 feet per week for each week following the peak until the end of the growing season, defined as September 30

The use of the term "peak" in this analysis refers to the maximum stage that satisfies these criteria, and not to the maximum annual stage or maximum stage during the specified period.

The peak stage, as defined above, is determined for without- and with-project conditions by analyzing the mean daily flow data sets based on the two criteria. For this analysis, an iterative procedure is required that identifies a peak discharge within the seasonal range, and then tests to see if it meets the recession criterion over the growing season. This step is probably best accomplished using a rating curve at each cross section. The iterative procedure moves to the next lowest mean daily flow value in the seasonal range if the recession criterion is not met. The iterative procedure results in a annual peak stage based on the rating curve that meets the two criteria. The peak stages for each year are used in an annual frequency analysis to define a stage at each cross section that corresponds to a 40-year return period for the without- and with-project condition. (The "40-year return period" applies to the qualifying germination flows, not to the set of annual peak flows.)

Potential Application in DTMs and GIS. The peak stage at each cross section, as defined above, is used in the DTMs to define an upper boundary for successful germination and establishment for vegetation types for which this relationship applies. The boundary is used to map suitable zones by vegetation type in the GIS.

Sub-Element A-4. Scour Regime of Riparian Zones

Required Hydrologic and Hydraulic Information. For the first option described in Section 2:

Stage-discharge rating curves at each cross section for discharge with a 10-year return period.

Depth of flow at existing vegetation boundaries at each cross section for the existing 10-year flow.

Locations at each cross-section that have the same flow depths but for the projected 10-year return flow.

This relationship is used to determine the predicted change in vegetation zones based on a change in hydrologic or hydraulic conditions. Although based on the physical process of scour, scour potential associated with specific hydraulic parameters (e.g., velocity, depth, energy slope, shear stress) is not directly computed. This approach was selected to avoid difficulties resulting from the high degree of uncertainty in calculating shear stress at particular locations within a complex channel, and the variability in resistance of vegetation to shear in a wide range of topographic, geomorphic, and substrate conditions. The approach therefore focuses on relative change in zone boundaries, using the existing conditions as a baseline. Field mapping of the zone boundaries, or determination from aerial photography, is required to establish this baseline. The without-project condition is determined by this mapping.

The existing vegetation zone boundaries are established by field mapping, and flow depths during the 10-year return period flow at each boundary at each cross section are determined using the hydraulic model. Stage for the with-project 10-year flow return period flows at each cross-section is also determined using the hydraulic model. Locations within the each cross-section having the same depths of flow under the with-project 10-year flow as the boundary depths for the without-project 10-year flow are identified. These new locations are inferred to represent the predicted with-project locations of the vegetation boundaries.

Potential Application in DTMs and GIS. The vegetation type boundaries for without-project and with-project conditions are developed on the DTMs and compiled in the GIS. Relative change is mapped and quantified in the GIS.

Sub-Element A-5 Scour and Inundation of Active Channel Habitat

Required Hydrologic and Hydraulic Information.

Highest discharge meeting timing and duration criteria for without-project and with-project data sets.

Stage-discharge rating curves at each cross section for discharges during low-flow months and for a 10-year return period.

Depth of flow at existing vegetation boundaries at each cross section for the existing 10-year flow.

Locations at each cross-section that have the same flow depths but for the projected 10-year return flow.

Analysis requirements for this relationship are similar to A-4, except that discharges and stages for flows meeting specified seasonal duration during low-flow months are also analyzed. The need for seasonal duration analysis requires the use of mean daily flow data sets for the without- and with-project conditions. From these, the highest discharges in the period of record for the without-project and with-project conditions are identified. Stages corresponding to these discharges are determined from low-flow rating curves for each cross-section. Using the DTM, the growing-season inundation zones is developed from these stages.

These without-project and with-project boundaries are compared to boundaries developed by the same methodology described for sub-element A-4, the latter depicting the boundary between the riparian scrub zone and the riverwash zone based on scour considerations. Finally, the inundation zone boundary and the scour zone boundary are compared at each cross-section, and the highest elevation is selected in the GIS. Thus, a single boundary for the active channel habitat, for both without-project and with-project conditions, is determined.

Potential Application in DTMs and GIS. The active channel habitat boundaries for without-project and with-project conditions are developed on the DTMs and compiled in the GIS. Relative change is mapped and quantified in the GIS.

Aquatic Element

Sub-Element I, E-1 In-Channel Rearing Habitat Abundance

Spawning Gravel Supply and Rejuvenation

Required Hydrologic and Hydraulic Information

Annual frequency of flows required to move bed material suitable for spawning.

Annual frequency of flows required to recruit bank materials suitable for spawning.

This relationship requires identification of peak discharges in specified reaches necessary to transport bed materials and erode banks for the purpose, of supplying and rejuvenating suitable spawning gravels to the channel. Incipient motion analysis is used to determine the bed and bank velocities required to move sediment of a specific size. An average channel velocity causing motion is then inferred from typical channel geometry, and an associated discharge is determined from hydraulic geometry at typical cross-sections (i.e. stage-discharge-velocity rating curves). The annual frequency associated with this discharge is determined from flood frequency curves for the without- and with-project conditions.

Potential Application in DTMs and GIS. The DTM is used to determine hydraulic geometry typical of the reaches of interest. Model outputs are change in sediment mobilization frequency in various reaches and would not involve spatial data in the GIS.

Channel Complexity and Instream Woody Material (IWM) Recruitment

Required Hydrologic and Hydraulic Information

The change expected from a proposed project in the 1.5-year and 5-year peak discharges.

This relationship requires a determination of the change in the 1.5-year and 5-year peak discharges associated with a proposed project. These discharges would be computed from the historical and synthesized daily flow datasets. Model output would be change in discharge between without-project and with-project conditions for these two return periods. Channel complexity and IWM recruitment is considered to change in direct relationship (increase, no change, or decrease), but a functional relationship is not available.

Potential Application in DTMs and GIS. The model output is a change of rate in each of specified affected geomorphic reaches (Table A-5). The DTM and GIS would not be used for this assessment.

Overhead Cover

Required Hydrologic and Hydraulic Information.

The relationship between the lower boundary of the riparian vegetation zones and the average August water surface level.

This relationship requires comparing two boundaries. The lower edge of the riparian zone is defined by the upper limit of active channel habitat as described in terrestrial Sub-Element A-5. The average August water surface level is determined in the same manner as the average September water surface level in terrestrial Sub-Element A-2.

Potential Application in DTMs and GIS. The two boundaries are determined at each cross section and mapped in the DTM. Without-project and with-project proximity of the boundaries are determined in the GIS by reach spatially and through generation of a proximity statistic.

Sub-Element II, B-1 Floodplain Spawning Habitat Abundance

Required Hydrologic and Hydraulic Information

Peak stages in floodplains and flood bypasses meeting specified criteria for timing, duration, and return period; and the years in which they occur.

Potentially vegetated portions of floodplains and flood bypasses inundated at these peak stages.

This relationship requires estimation of long-duration inundation in the spawning period for splittail. More frequent inundation is beneficial for populations, and very infrequent inundation results in the unsuitability of an area to support splittail populations. Inundation meeting the specified seasonal duration criteria for a 3-year return period is considered adequate to support healthy populations. Inundation meeting the criteria but having a greater return period is considered inadequate.

The data analysis requirements are similar to that for terrestrial sub-element A-3, including specification of a season and duration of biological significance, and analysis of mean daily flow data sets to produce a stage that corresponds to the specified frequencies. The analysis results in peak stages for with-project and without-project conditions that correspond to the 3-return period and:

1) occur between February 1 and May 31, and
2) have a duration of at least 21 days.

The peak stages are defined at each cross section.

Potential Application in DTMs and GIS. The peak stages, defined as described above, are used in the DTMs to define boundaries. The boundaries are mapped in the GIS and overlain with estimations of potential riparian/wetland zones (from the terrestrial model element) to define zones of suitability for spawning.

Sub-Element II, C-1. Floodplain Rearing Habitat Abundance

Required Hydrologic and Hydraulic Information

Peak stages in floodplains and flood bypasses meeting specified criteria for timing, duration, and return period; and the years in which they occur.

Potentially vegetated portions of floodplains and flood bypasses inundated at these peak stages.

The analysis requirements for this relationship are very similar to those for Sub-Element II, B-1. The relationship is directly linked to B-1, in that the inundation for rearing habitat must occur in the same year as the inundation for spawning habitat. The analysis requires identification of the years in the mean daily flow data sets in which suitable spawning areas exist from the analysis described for B-1. These years are analyzed to determine if they meet the criteria for rearing habitat in the same reach. The peak stage associated with a duration of at least 56 days occurring in the period between December 1 and May 31 with a return period of 3 years is determined for each cross section.

Potential Application in DTMs and GIS. This elevation is used in the DTM to define a boundary and a water surface for without-project and with-project conditions. These zones are mapped in the GIS and are compared to the potential vegetation zones, developed as described in the terrestrial model element, to determine suitable rearing areas under without-project and with-project conditions.

Sub-Element II, C-3. Habitat Connectivity

Required Hydrologic and Hydraulic Information.

Area of flood recession ponds in the rearing habitat zones that meet specified depth criteria, and the tributary area that drains through the ponds.

Frequency that floodplain inundation is of sufficient duration to prevent isolation of recession ponds before April 30 and before May 31.

The required flood recession pond data is obtained primarily in DTM and GIS analysis, as described below. That analysis identifies an elevation at which recession pond isolation occurs in the reach associated with each cross section. Using the hydraulic geometry at each cross section, the discharge associated with recession pond isolation is identified. The without-project and with-project daily flow datasets are then queried to determined the frequencies with which the isolation discharge is exceeded on April 30 (for Chinook salmon rearing) and on May 31 (for splittail rearing). Change in the frequency of pond isolation on these dates is therefore identified.

Potential Application in DTMs and GIS. Floodplains are analyzed using the DTMs in the GIS to determine the area of closed, or nearly closed depressions with depth at closure exceeding one foot. The area of closed depressions relative to floodplain area is compiled in the GIS for the reach associated with each cross section. As noted above the highest elevation at which pond isolation occurs in each reach is identified, for use in the frequency analysis described above . In addition, the areas draining through the closed depressions (watershed area of each depression) are analyzed and compiled on a percent of floodplain basis using the DTMs and GIS. Without-project and with-project floodplain morphology can therefore be compared in terms of fish stranding potential.

AVAILABLE HYDROLOGIC AND HYDRAULIC INFORMATION FROM PRESENT STUDIES

Hydrologic and hydraulic analyses are presently being conducted for the Comprehensive Study that will provide the tools to select and evaluate actions for flood-damage reduction and environmental restoration in the study area. In general, these analyses are focused on large flood events with the potential to cause significant damage. This section briefly describes the studies presently being conducted and their potential applicability to the hydrologic and hydraulic information requirements of the EFM.

Hydrologic Studies

The hydrologic and hydraulic studies presently in progress for the Comprehensive Study include generation of hypothetical unregulated n-year hydrographs, routing of the unregulated hydrographs through the major reservoirs in the system, and hydraulic modeling of the computed n-year regulated hydrographs. The hypothetical hydrology is based on analysis of period-of-record streamflow data, adjusting these data as necessary to produce unregulated flow frequency curves. Unregulated flows are being computed at 21 tributary and 4 mainstem locations in the Sacramento

Basin (27,000 square miles), and 22 tributary and 4 mainstem locations in the San Joaquin Basin (20,000 square miles).

The unregulated n-year hydrographs are being developed by considering 19 historical storm patterns to produce two storm centerings. The tributary centerings are designed to produce the highest flows on individual tributaries, with extreme flows possible on a single tributary. In general, total runoff volume and system-wide effects are relatively low for this centering. The mainstem centering is designed to simulate a system-wide storm event, producing high flows in the entire system, with the associated high runoff volumes. The centerings are converted to hydrographs by distributing runoff volumes into hourly pattern hydrographs and routing the flows from each tributary to the mainstem.

The unregulated n-year hydrographs are routed through the reservoirs using HEC-5 based on operational criteria. The effects of 28 headwater reservoirs and 9 lower basin reservoirs are being modeled in the Sacramento Basin, and 19 headwater reservoirs and 18 lower basin reservoirs are being modeled in the San Joaquin Basin. The HEC-5 reservoir routings result in regulated n-year hydrographs for use in the hydraulic models of the system. Hydrographs are being produced for the 2-, 10-, 25-, 50-, 100-, 200-, and 500-year events.

In addition to the computation of n-year hydrographs for flood routing, the Comprehensive Study has compiled available hydrometeorlogic data in the study area in Data Storage System (DSS) format. These data were used to produce grid-based rainfall-runoff models for the headwater basins. Although not presently being used to estimate flows for flood routing, these models will be used in the future in operational models of the reservoirs. The study will also produce a continuous simulation model of reservoir operations using the entire daily flow period of record, and a reservoir optimization model.

Hydraulic Studies

The n-year regulated hydrographs described above are being used as input to hydraulic models of the Sacramento and San Joaquin Basins. Channel and floodplain geometry for the hydraulic models is based on bathymetric surveys and aerial photogrammetry from 1995 (Butte Basin), 1997 (Sacramento Basin), and 1998 (San Joaquin Basin). The vertical accuracy of the bathymetric surveys is approximately 0.4 feet. The topographic surveys have a contour interval of 2.0 feet and a vertical accuracy of 1.0 feet. In the Sacramento Basin, the models include over 500 river miles with approximately 3000 cross sections spaced at 1000 to 2000 feet. In the San Joaquin Basin, the models include over 400 river miles with approximately 1200 cross sections spaced at 1000 to 2000 feet.

Hydraulic characteristics in the system are being modeled using a combination of an unsteady flow one-dimensional model (UNET) of the main channel, and a 2-dimensional model (FLO-2D) of the overbank flows. The UNET model is used to analyze potential levee failure points by using a likely failure point defined by the type of levee material on a reach basis. Breakout flows from UNET are then routed in FLO-2D to generate floodplains. Floodplains are being mapped for the 10-, 50-, 100-, 200-, and 500-year events. Floodplains are delineated for both storm centerings described above, and then mapped as a composite of the results.

Applicability to EFM

The hydrologic studies presently being conducted provide flood frequency relationships for key index points in the systems. The hydraulic models provide flood routings of these flows, producing discharge, depth, velocity, and other hydraulic characteristics at each cross section. These results are directly relevant to EFM relationships that require annual flood frequencies and flows.

The compiled streamflow gage data and the continuous simulation period of record models being produced for the study will provide a mean daily flow data set for much of the system, and a potential means to simulate operational modifications at the reservoirs. Additional synthesis will be required to produce representative mean daily flows in each reach of the system. Existing operational hydrologic models (e.g., CAL-SIM) may be useful for synthesizing flows, although conversion from a monthly to daily time step would be required.

The existing hydraulic models are applicable to EFM requirements for defining river stages for flood events. For lower flow conditions, model refinement would be necessary to ensure accuracy. In cases where EFM analysis requires multiple model runs to determine stage at various flows or different flows at individual cross sections, conversion of the unsteady channel model to a steady state model such as HEC-RAS may facilitate the runs.

In general, the existing studies will not produce durations, frequencies, stages, or timing associated with specific ecological criteria as stated in the functional relationships. These metrics will be generally be produced for EFM relationships by analyzing the observed and/or synthesized mean daily flow sets (or other hydrologic information) based on specified criteria. The results of these analyses will then be used in hydraulic models or computations, and in DTM/GIS analysis as described above.

Summary of Hydrologic and Hydraulic Information Needed for the Relationships

Table C-1 compiles the data hydrologic and hydraulic information required to support EFM relationships, potential data sources and analysis methods, the potential application of analysis results to obtain EFM outputs, and the availability of required information from hydrologic and hydraulic studies already in progress. This summary presents initial assessment of these topics only, based on the relationships presently defined. The feasibility of the data collection and analysis described, and its potential application in DTM and GIS tools requires refinement as the relationships are tested and further developed in pilot studies.

Table C-1. Summary of Hydrologic and Hydraulic Information for EFM Relationships

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Sub-Element/ Relationship	Information Required	Data Sources and Analysis Required	Application Methods	Availability from H&H Studie
rrestrial A-2. Depth Water Table	Groundwater level in August	1) Available groundwater data 2) Field measurements 3) September river stage-low flow model or rating curve	DTM used to compute depths; zones associated with potential vegetation types developed in GIS	None
rrestrial A-3. Flood ents Suitable for ant Germination and tablishment	Annual maximum stage during period mid-April to mid-Aug that meets recession criteria	1) Streamflow gage records 2) Synthesized streamflow 3) Stage-discharge rating curves at each model cross section 4) Computer analysis to develop stage-frequency relationship	DTM used to identify surfaces below the computed 40-yr return period stage; potential germination and establishment area developed in GIS	1) Streamflow gage records compiled for the study area; 2) Hydraulic model available to develop rating curves
rrestrial A-4. Scour gime of Riparian nes	1) Stage and discharge for 10-year return-period flow 2) Flow depths associated with existing vegetation boundaries 3) Corresponding depths for same return period flow for with-project conditions	1) Stage-discharge rating curves at each model cross section 2) Flood frequency analysis	DTM used to define boundaries for existing and with-project conditions; boundaries compiled and compared in GIS; relative differences mapped	1) Hydraulic model available for development of stage-discharge curves 2) Flood frequency relationships developed for major reaches for the without-project condition
rrestrial A-5. Scour d Inundation of tive Channel bitats	1) Highest discharge meeting timing and duration criteria 2) Stage and discharge for 10-year return-period flow 3) Flow depths associated with existing vegetation boundaries 4) Corresponding depths for same return period flow for with-project conditions	1) Streamflow gage records 2) Synthesized streamflow 3) Stage-discharge rating curves at each model cross section 4) Computer analysis to develop stage-frequency relationship	DTM used to identify surfaces below the computed stages; riverwash zone developed in GIS	1) Streamflow gage records compiled for the study area 2) Hydraulic model available for development of stage-discharge curves; requires refinement for lo flow conditions 3) Flood frequency relationships developed for major reaches for the without-project condition
uatic I, E-1. In-annel Rearing bitat	1) Annual frequency of flow that moves bed material and recruited bank material with grain sizes suitable for spawning 2) Change in 1.5- and 5-year discharge anticipated due to a project 3) Average August water level	1) Bed and bank material characteristics by reach 2) Peak discharges required to mobilize bed material and recruit gravel from banks 2) Flood frequency analysis	DTM used to define boundary of average August water level, GIS used to map and quantify areas in relationship to potential riparian zones	1) Hydraulic models available to use in determination of discharge required to mobilize bed materia 2) Flood frequency relationships developed for major reaches for the without-project condition

Sub-Element/ Relationship	Information Required	Data Sources and Analysis Required	Application Methods	Availability from H&H Studie
uatic II, B-1. odplain Spawning bitat Abundance	1) Peak stages in floodplains and flood bypasses associated with specified return periods and seasonal durations, and years in which they occur 2) Potentially vegetated areas inundated at these peak stages	1) Streamflow gage records 2) Synthesized streamflow 3) Stage-discharge rating curves at each model cross section 4) Computer analysis to develop stage-frequency relationship	DTM used to identify surfaces below the computed stage; suitability zones developed in GIS	1) Streamflow gage records compiled for the study area 2) Hydraulic model available for development of stage-discharge curves
uatic II, C-1. odplain Rearing bitat Abundance	1) Peak stages in floodplains and flood bypasses for years that meet criteria for timing, duration, and return period, and years in which they occur	Same as above	DTM used to define boundaries using peak stage and maximum depth criteria; suitability zones developed in GIS	Same as above
uatic II, C-3. Habitat nnectivity	1) Area of flood recession ponds in rearing habitat zones that meet depth criteria, and tributary areas that drain through ponds 2) Frequency that floodplain inundation duration prevents pond isolation before specified dates.	1) Same as above	DTM and GIS used to define areas of closed depressions within rearing habitat zones, and tributary area draining through closed depressions	Same as above